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FOVEAL LENS

SIZE REDUCTION STUDY

McDonnell Aircraft Company
McDonnell Douglas Corporation
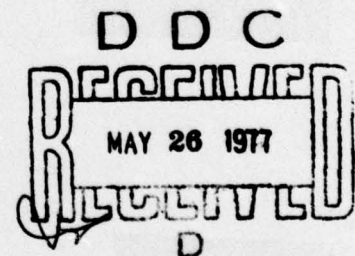
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April 1976

TECHNICAL REPORT AFAL-TR-76-6
Final Report for Period June 1975 - November 1975

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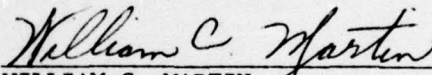**WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433**

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This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This report was prepared by McDonnell-Douglas Corporation, St. Louis, MO. The work was performed under Air Force Contract F33615-75-C-1294, Project 76620711. The program was under the technical direction of William C. Martin, AFAL/RWI, AF Avionics Laboratory, Wright-Patterson Air Force Base, OH.

This report has been reviewed and is approved for publication.

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AF Project Scientist
AFAL/RWI

FOR THE COMMANDER

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Reconnaissance & Weapon Delivery Div.
Air Force Avionics Laboratory

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Technical feasibility is established of miniaturizing the MCAIR nonlinear or foveal lens. The original lens fabricated under a Navy contract proved to be too large and heavy for USAF applications.

Theoretical limits of miniaturization are developed by establishing preliminary optical designs for lenses with progressively smaller clear aperture diameter and comparing performance with system requirements.

20. ABSTRACT (Concluded).

The results show that a 50% size reduction is possible with no loss in optical performance. The resulting 4 inch diameter F/3 lens can be fabricated of either glass or plastic optical materials. Optical performance of the lens is such that it can support up to 4x magnification of its image to achieve a zoom capability that is desirable for detailed target identification.

Further size reduction to a 2 inch diameter is shown to be technically feasible but with a penalty of less resolution or higher F/number. The former will limit zoom magnification possible, while the latter will reduce daylight operating time. A higher technical risk is associated with this level of miniaturization.

PREFACE

This report contains studies and analyses which establish the degree of miniaturization possible for the MCAIR non-linear or variable acuity lens. This lens, previously proven feasible in a large size under Navy contract, has great potential to reduce the required bandwidth of remote viewing systems.

This effort was administered under direction of the Air Force Avionic Laboratory, Dayton, Ohio. The program monitor was Mr. William C. Martin.

TABLE OF CONTENTS

62728   95-

LIST OF ILLUSTRATIONS

62728

95

62728

Section I

INTRODUCTION AND SUMMARY

In 1969-1970 MCAIR conceived a unique technique for bandwidth reduction for remote viewing. This concept employs extreme non-linear optical components to divide the sensor's optical field of view into variable size resolution elements similar to that of the human visual process. When these picture elements are sent to a remote location and arranged (displayed) in the same geometry as received by the sensor, the resulting reconstructed picture will fully support human vision in both field of view and resolution. Total picture elements are such that transmission can be accomplished easily within conventional TV video bandwidths.

The key element of this Variable Acuity Remote Viewing System (the non-linear or "foveal" lens) was constructed and demonstrated during 1973 under contract to the U.S. Navy. This lens exceeded requirements for performance but was too large and heavy for USAF applications. The effort described in this document establishes technical feasibility of miniaturizing this lens and predicts its physical parameters, performance, and limitations when coupled to a solid state charge coupled sensing array.

This was accomplished by utilizing the computer design and optimization program, developed for our existing lens, to derive preliminary optical designs for smaller clear aperture diameters and the extended spectral range required for the silicon detector array. The theoretical performance of these designs are evaluated as a function of the performance requirements to determine the degree of miniaturization possible.

The results of this analytical effort far exceeded expectations. Size reductions over 50% are shown to be theoretically possible with no loss in optical performance. The 4 inch diameter F/3 lens resulting from this effort can be fabricated of either glass or plastic optical materials. Use of plastics for the aspheric elements can lead to significant production cost reductions. Optical performance of the lens is such that it can support up to 4x magnification of its image to achieve a zoom capability for detailed target identification.

Further size reduction to a 2 inch diameter is shown to be technically feasible but with a penalty of less resolution and higher F/number; the latter resulting in less daylight operating range. However, a higher technical risk is incurred with this configuration.

1

Section II

APPROACH

The Foveal Lens Miniaturization Study followed the sequence shown in Figure 1. Our existing lens parameters plus the customer recommended CCD characteristics furnished inputs to the "Input Definition" phase of the study. This phase, described in detail in Section 3 of this report, defined all information required to initiate the "optical design studies." This includes the fixed or constant inputs of field of view, distortion, image size, focal length, and wavelength. Also established in this phase are bounds for the tradeoff parameters of F/number, optical quality, and optical materials. In addition, practical design constraints are developed here such as minimum element size, mechanical considerations for materials, and fabrication/cost considerations.

The above data plus the computer optimization program developed for our existing lens supplied necessary inputs for the "Optical Design Study" discussed in Section 5 of this report. In parallel with this phase, a system performance analysis model was developed and exercised to continually assess the impact of lens quality outputs of the design studies on end-to-end system performance. This model, described in Section 4, outputs minimum resolvable contrast as functions of spatial frequency (resolution), lens quality, and display capability.

The heart of the study, the Optical Design Phase, begins by reducing the size of our existing lens while maintaining the same optical materials and optical spectral range. As this visual spectrum miniaturized lens evolved, a design study of the optical relay (identified as a requirement in Section 3) was conducted.

As confidence was developed in the modified computer design program, the optical spectral range is extended into one more compatible with the silicon CCD detector. At this point, materials are still maintained as glasses because of the wide range of dispersions and indices of refraction available in these materials. This simplifies the optimization by allowing continuous computer modeling of material constants. As the program converges on an optimized configuration, constraints are placed on materials characteristics so they match available glass types. After reoptimization of this design for specific glass types, it was evaluated over the effective response range of the silicon detector. Next, a plastic optical design was developed. To accomplish this, constraints were placed on the program to operate with plastic material optical constants for the aspheric elements (cost/performance tradeoffs indicate that spherical elements should be glass). At this point, two optical designs existed - one for plastic aspherics and one for glass aspherics.

In Section 6 of this report, the two final designs are assessed with respect to system performance, degree of miniaturization achieved, fabrication considerations, and cost. Finally, our recommendations are presented for an approach to lens development.

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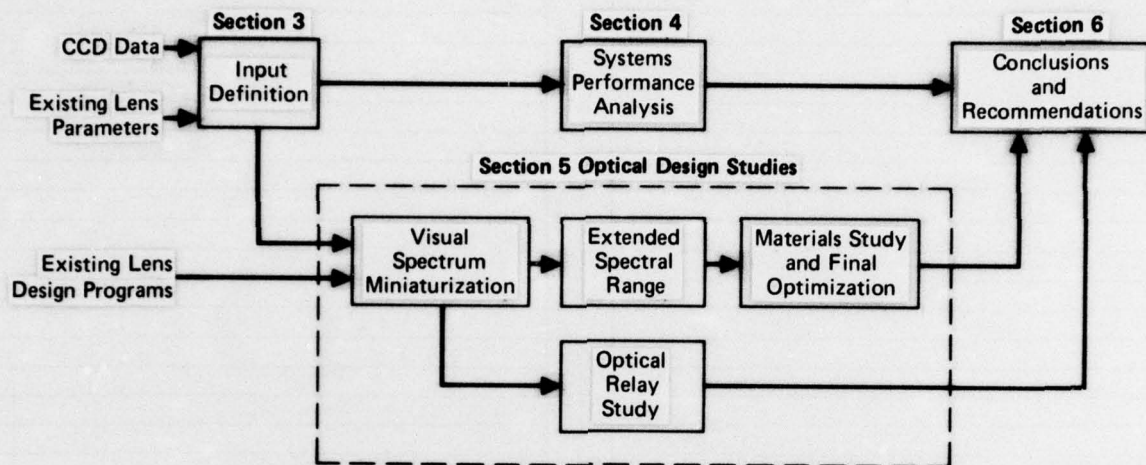
Figure 1   Foveal Lens Miniaturization Study Approach

Section III

INPUT DEFINITION

This section summarizes studies and analyses required to define inputs before actual lens design could be initiated. These inputs are basically of two distinct types - those that are constant and will not be varied throughout the study and variables (usually referred to as tradeoff parameters).

A. FIXED PARAMETERS

Constant parameters are field of view, distortion, image size, focal length, and wavelength. These are defined as follows.

1. Field of View

The basic RVS concept utilizing the foveal lens employs a full hemispherical coverage (180°). In order to study benefits of reducing this angular coverage, the curve of Figure 2 was generated from parametrics of our existing lens. Note only a 10% size reduction could be achieved by reducing coverage from 180° (+90°) to 90° (+45°). In view of this, the 160° FOV presently mechanized in our existing lens was established as a design requirement for the miniature lens.
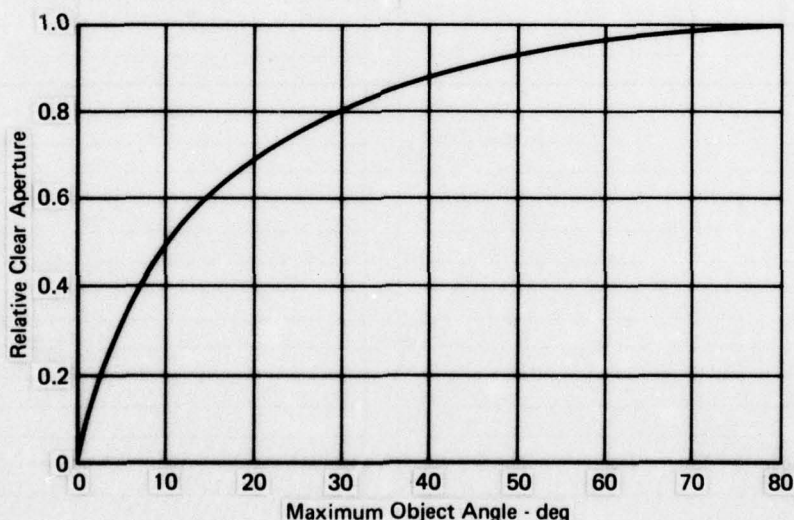
Figure 2   Lens Size as a Function of Angular Coverage

2. Distortion Function

During initial design of our existing 2 inch focal length lens, a close match to the eye acuity function was used to compute the required lens distortion function. During that design effort this function was revised slightly because it was impossible to achieve the required resolution at very small field angles. This modified function is believed to be the closest match to human vision technically possible.

4   62728

Both the original and revised functions are shown on Figure 3. Note how the revised function falls below the synthesized eye function at object field angles less than 0.5°. To see how well the lens follows design requirements, the lens design program for our existing lens was exercised to determine exactly what distortion was being achieved in the design. To supplement this, actual measurements were made on the lens by reprojecting a linear grid through the lens on a spherical surface. This image was photographed and grid line separation measured to compute the distortion function. These results are also shown on Figure 3. Over the range of measurement (±30°), the measurements agree quite well (within accuracy of the measurement technique) with the computer design predictions. Both deviate somewhat from the initial input data, but the deviation is small.
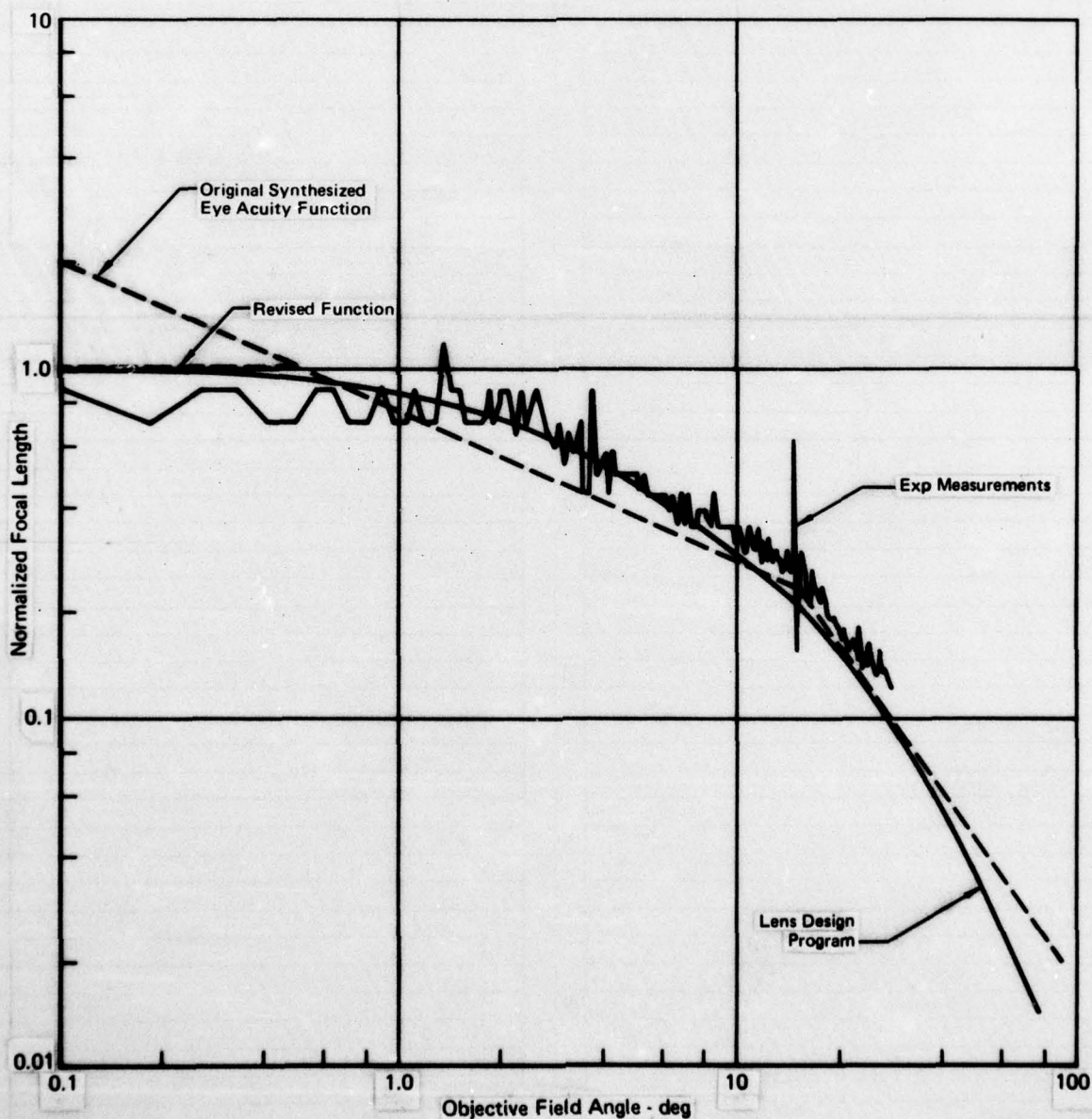
Figure 3 Lens Distortion

62728

Based on these data it seems best to use the computer design predictions for the distortion function during foveal lens miniaturization studies. Reasons for this are:

o The computer design function is believed to be the best compromise to the original design data. It was achieved with great difficulty and probably represents the maximum agreement achievable within practical constraints.

o Experimental data appears to follow this data better than the original design data.

o A lens designed to the computer predicted distortion function will be compatible with equipment designed with the existing lens. For example, a sensor fabricated with the miniature lens will be compatible with the ONR projection display system.

3. Image Size

The image size is governed by the CCD array geometry. As specified in the SOW, the RCA SID 51232 was used to establish image size requirements. This array requires an image size of 7.31 x 9.75 mm. In order to utilize this array in the most efficient manner, an image diameter larger than the vertical raster dimension was utilized. This measurement was arrived at as shown below.

Because of eyebrow vignetting when viewing upward and the normal lookdown interference of instrumentation, controls, etc., 80° (+50 to -30) is generally considered sufficient. Referring to Figure 4 (the foveal lens transfer characteristics in terms of image height as a function of object angle), 80° total object can be achieved with 83.65% of the total image height. This layout is shown in Figure 5. To produce this geometry, the foveal lens image height must be:

$$H = \frac{7.31}{.836} = 8.74 \text{ mm.}$$

It should be pointed out that the 80° vertical viewing limit created in the attempt to utilize more of the CCD elements occurs only at zero azimuth. This increases rapidly as azimuth angles increase.

4. Focal Length

The on-axis focal length, $f(0)$, is determined directly from image height as follows. As computed in the previous paragraph, the image height for 80° is

$$h(80) = \frac{8.74}{2} \text{ mm} = 4.37 \text{ mm}$$

where h is the image height from the lens optical axis. The lens distortion equation on-axis is:

$$f(0) = 5.44 \, h \, (90) \qquad \qquad \text{Eq. (1)}$$

where $h(90)$ is image height at $\theta = 90°$.

6

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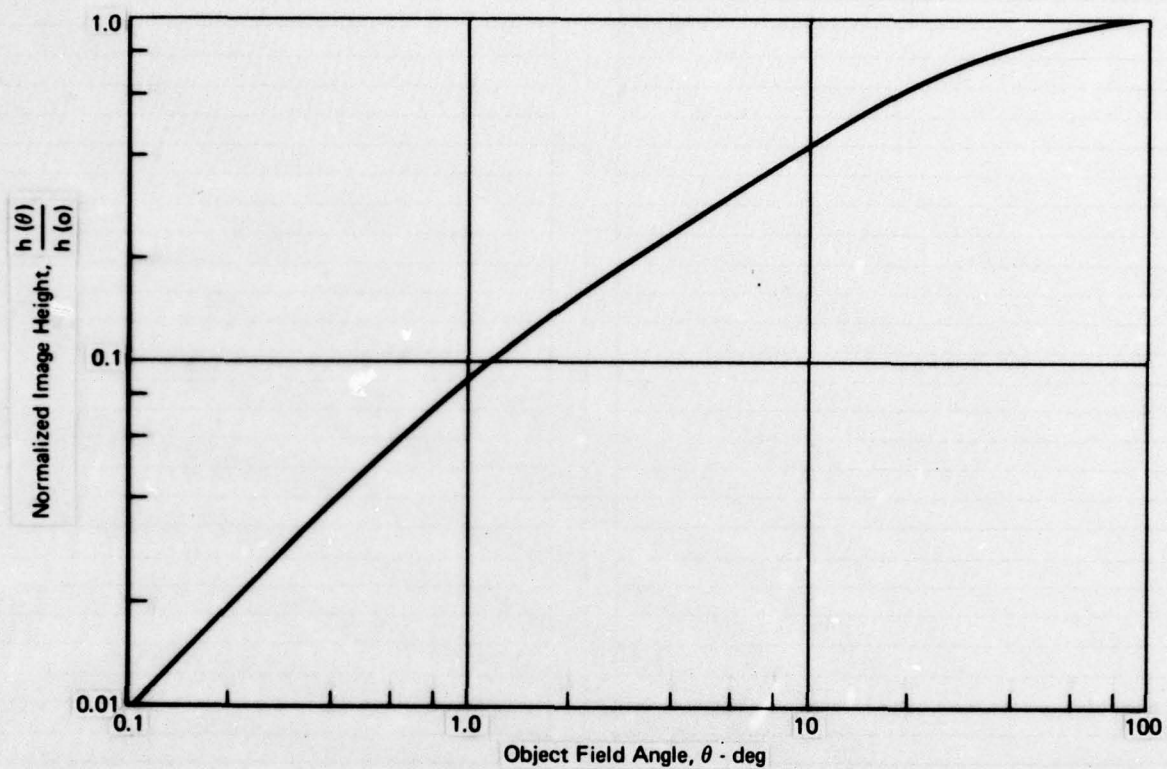
Figure 4   Lens Transfer Characteristics
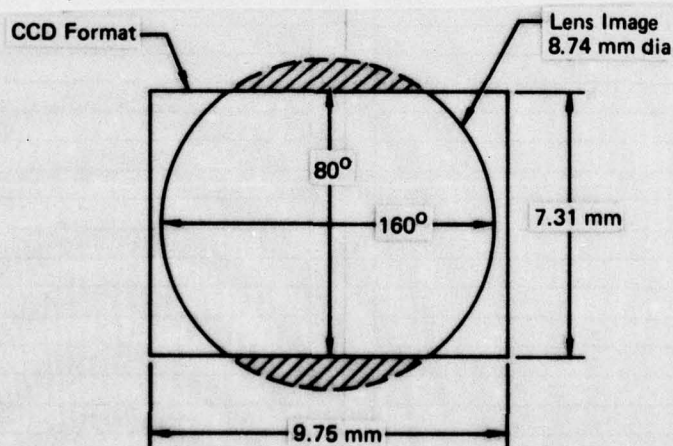
Figure 5   CCD/Lens Image Geometry

7

From the lens transfer characteristics (Figure 4), if

$$h(80) = .9787 \ h(90)$$

$$h(90) = \frac{4.37}{.9787} = 4.46 \ mm.$$

Then from Equation (1)

$$f(0) = 5.44 \times 4.46 = 24.29 \ mm.$$

The proximity of this value to 1 inch or 25.4 mm led us to consider pushing the focal length slightly to this value. This was advantageous because our computer design program is based on unity focal length, and scaling of results would be unnecessary. It will be seen later that minor focal length adjustments can be easily made through simple adjustments of optical components.

5. Wavelength

The spectral response requirements of the foveal lens are dictated by the spectral response of the CCD array. The response of the RCA unit is shown in Figure 6a. Also shown on this plot is the wavelength band used to optimize our existing lens. This spectral band was used to give best performance in the visual spectrum. It is obvious from this figure that a large mismatch exists between the lens design and CCD spectrums. Actually, optical filtering of input radiation would be required to assure maximum lens performance. The result would be greatly reduced sensitivity as is shown by the dashed line. Since our design program was working properly on the reduced spectrum, we felt it would be best to study reducing the lens size using the existing visual spectrum. After this was completed, the spectral range would then be gradually shifted to the longer wavelength region. This was initially accomplished to the region shown by the double cross-hatched region of Figure 6b. Finally, the longwave end of this spectrum was increased to 960 nm to reach the half sensitivity limits of the CCD array. With this final criteria, utilization of at least 80% of the CCD's sensitivity is assured.
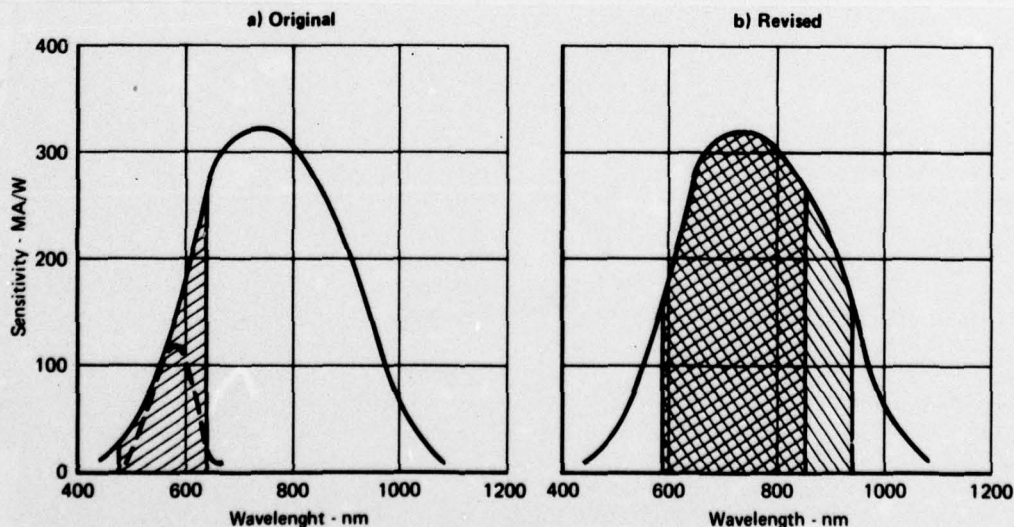
Figure 6 Lens Spectral Design Requirement - RCA SID 51232

8

B. TRADEOFF PARAMETERS

Tradeoff parameters to be used in the lens design study are F/number, lens optical quality, and materials. In general, the task at this point is to establish bounds or the range of these variables.

1. F/Number

Obviously, lens size will be minimum with the smallest possible collection aperture or largest F/number. The task here is, therefore, to determine the largest F/number that will be acceptable in meeting mission conditions. To determine this, scene brightness requirements as a function of F/number were computed for the CCD array. In order to assure that the non-linear nature of the foveal lens does not influence photometric calculations, these equations were derived as follows: Referring to Figure 7, the luminous flux entering the Aperture D from an infinitesimal patch of ground area, dAg is

$$F = B \omega \, dAg.$$

If the surface is a lambertian radiator, this flux will, by definition, falloff with cosine of the viewing angle, i.e.,

$$F(\theta) = B \omega \, dAg \cos \theta.$$

Now all the flux from dAg will be attenuated by lens transmission, ε, and fall on element of area, dA. Therefore, the illumination of the image is

$$E = \frac{\varepsilon F(\theta)}{dA} = \varepsilon B \omega \, \frac{dAg}{dA} \cos \theta. \qquad \text{Eq. (2)}$$
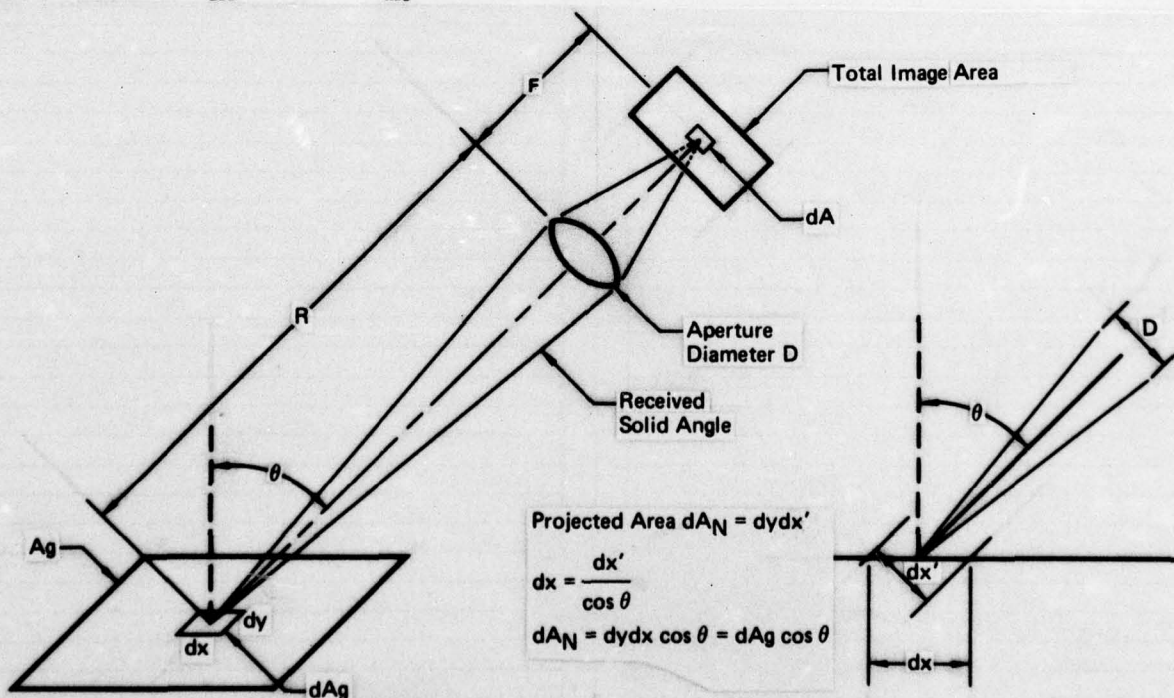
Figure 7   Sensor/Target Photometric Geometry

9

dA and dAg are related by simple geometry. Referring to Figure 7,

$$\frac{dA}{dA_n} = \frac{f^2}{R^2} \quad \text{and} \quad dAn = dAg \cos \theta.$$

By substitution,

$$\frac{dAg \cos \theta}{dA} = \frac{R^2}{f^2} \,.$$

Substituting this into Equation (2)

$$E = B\omega \, \frac{R^2}{f^2} \,.$$

By definition,

$$\omega = \frac{\pi D^2}{4R^2}$$

$$E = \epsilon B \, \frac{\pi D^2}{4R^2} \, \frac{R^2}{f^2} = \frac{\pi}{4} \, B \, \frac{D^2}{f^2}$$

$$E = \frac{\pi}{4} \, \epsilon \, \frac{B}{(F/No.)^2} \qquad \begin{array}{l} \text{E is in foot candles if} \\ \text{B is in lumens/steradian} - \text{ft}^2 \end{array}$$

If B is specified in foot lamberts, by definition of this unit

$$E = \frac{\epsilon B_{FL}}{4(F/No.)^2} \; \text{ft-candles} \qquad\qquad\qquad \text{Eq. (3)}$$

If ϵ is taken into account through a T number where

$$T_{No.} = \frac{F/No.}{\sqrt{\epsilon}}$$

$$E = \frac{B_{FL}}{4(T_{No.})^2} \qquad\qquad\qquad\qquad\qquad \text{Eq. (4)}$$

Now for the RCA CCD under study

$$E = .1 \; \text{ft-candle}$$

$$B_{FL} = .4(T_{No.})^2$$

To study how this relates to the real world, a 10% ground reflectance was assumed to obtain ground incident illumination.

$$E_g = \frac{B_{FL}}{.1} = 10 \, B_{FL}$$

$$E_g = 4(T_{No.})^2$$

Various $T_{Nos.}$ were computed from this equation and plotted on the conventional earth illuminance chart, Figure 8. The following conclusions can be reached from this figure.

o Nighttime operation cannot be achieved under any conditions unless the CCD can be made more sensitive.

o Good daytime performance between sunrise and sunset requires a T number in the vicinity of T = 2.8. Going to T = 1.4 buys very little performance improvement; while going to T = 5.6 would limit operation by several hours when operating under heavy clouds.

Based on the above analysis, an F/number of 2.8 or smaller will be considered acceptable. F/number will be approximately equal to T number for the foveal lens because of the high transmission verified in the existing lens.

2. Lens Quality

This parameter is undoubtedly the most difficult one to quantify. It is intimately tied to F/number as it impacts on lens size. Therefore, both of these parameters must be discussed together. As a starting point, the design program for our existing lens was examined very closely to estimate how F/number and image quality influence size. The key size impact was found to be the clear aperture of the first element. Estimates of these parametrics are shown on Figure 9. They are all extrapolated from one point - our existing lens using geometrical optical theory. This should be a valid assumption for the F/number range under consideration.

Figure 9 shows that if F/2.8 is desired in a lens approximately half the size of our existing lens, an optical quality representing a 20 micron maximum spread function width will be achieved in the image plane. This figure shows that another 50% size reduction could be achieved by further reduction of optical quality to 40 microns. Obviously, the question that must be answered is exactly what optical quality is really required. This can only be resolved through some level of systems analysis. In order to accelerate entry into the lens design phase, an estimation of lens quality was made based on modulation available at the absolute resolution limit of the CCD array. There are two identifiable limiting spatial frequencies that can be easily identified for a discrete array. They are one cycle per element spacing and one cycle per two element spacings. These bound CCD performance as the maximum and minimum spatial frequencies that are theoretically possible to detect. The theoretical justification for these values and their statistical probabilities will be discussed later. They arise from relative phasing of target spatial detail to element position in the array. For the RCA CCD, which has element spacing of $a = .0305$ mm,

11   62728   90
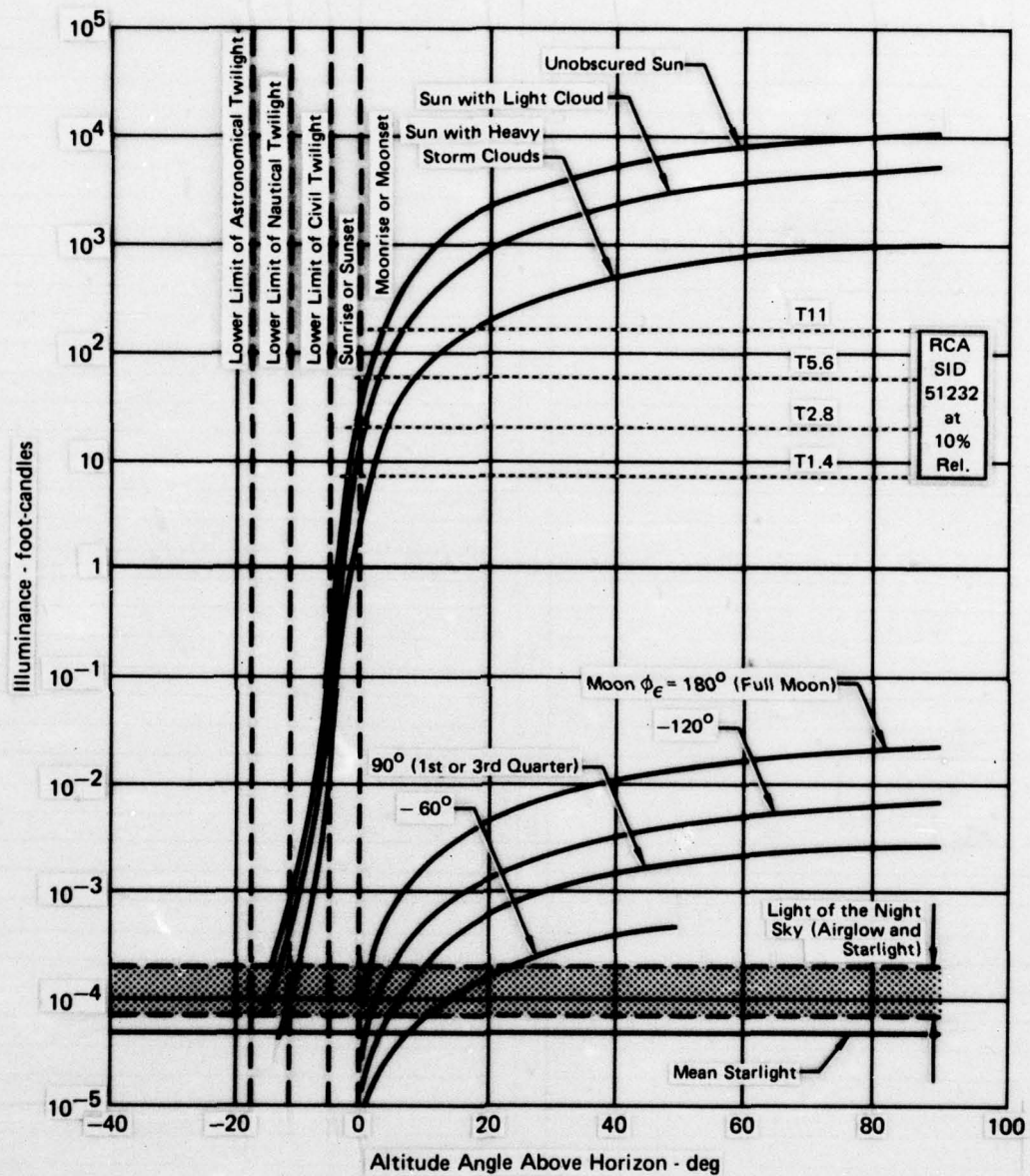
Figure 8   Earth Illuminance

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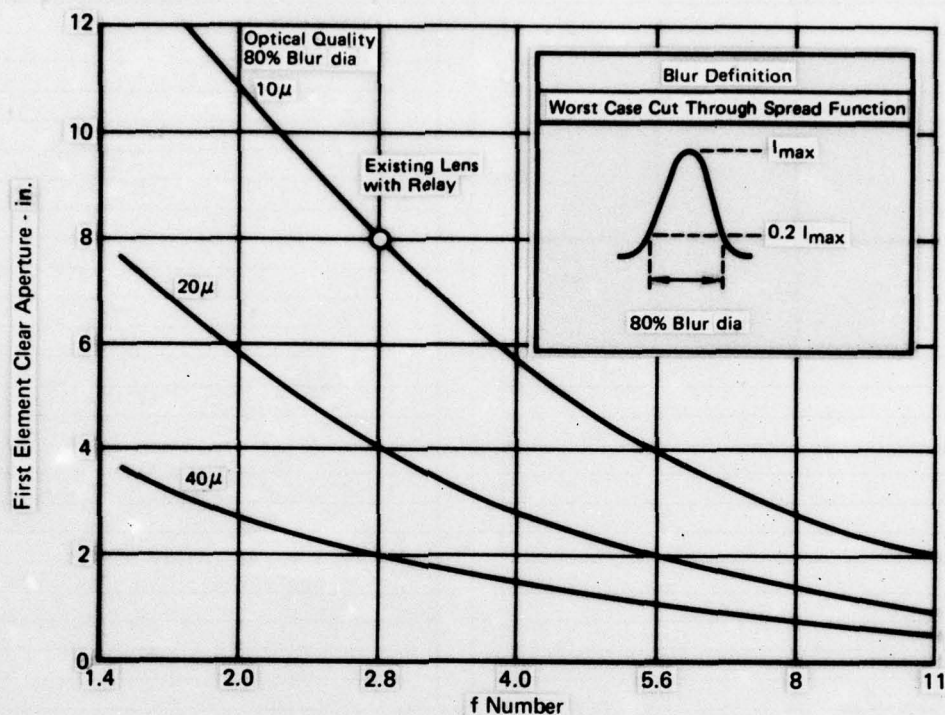
Figure 9 Theoretical Lens Size Parametrics
Effective Focal Length = 1 In.

$$S_{max} = \frac{1}{.0305} = 32.81 \ \frac{cycles}{mm}$$

$$S_{min} = \frac{1}{2 \times .0305} = 16.40 \ \frac{cycles}{mm} \ .$$

The lens MTF is estimated as follows. Review of blur plots indicate the worst case spread function cross sections are very nearly Gaussian in shape, i.e.,

$$I(x) = I_m \ e^{-1/2 \left(\frac{x}{\sigma}\right)^2} \qquad\qquad Eq.(5)$$

The value of sigma (σ) required to define this equation can be computed from our 80% blur circle diameter as follows. (See Figure 9.)

$$D_{(80)} = 2x \ (\text{when } I = .2 \ I_m)$$

From Equation (5),

$$.2 \ I_m = I_m \ e^{-1/2 \left(\frac{D_{80}}{2\sigma}\right)^2}$$

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Solving for sigma

$$\sigma = \frac{D_{80}}{3.59} \qquad\qquad \text{Eq.(6)}$$

The lens minimum MTF is derived from the maximum width spread function by taking the Fourier transform of Equation (5). The result is

$$\tau(S) = e^{-2\pi^2\sigma^2 S^2} \qquad\qquad \text{Eq.(7)}$$

where σ is defined by Equation (6), combining Equations (6) and (7),

$$\tau(S) = e^{-1.532\ D_{80}^2\ S^2} \qquad\qquad \text{Eq.(8)}$$

Now studying this at the maximum detector spatial limit

$$\tau(S) = e^{-1.532\ D_{80}^2\ (32.81)^2} \qquad (\text{Note:}\ \ D_{80}\ \text{must be in mm})$$

$$\tau(32.81) = e^{-1649\ D_{80}^2}. \qquad\qquad \text{Eq.(9)}$$

For the minimum spatial frequency, the equation is

$$\tau(16.40) = e^{-412\ D_{80}^2} \qquad\qquad \text{Eq.(10)}$$

Equations (9) and (10) are plotted in Figure 10. This figure indicates that a lens requirement of about 10µ would be desirable. A modulation between 85 and 95% would be available regardless of relative phasing of target/detector element detail. For an F/2.8 lens, Figure 9 shows that an 8 inch clear aperture lens would be required. This fact led us to consider a 20µ optical quality. There are several reasons for this besides the lens size reduction, i.e., the 4 inch clear aperture it produces. First and most important, past design experience has demonstrated that the worst case spread functions occur in the meridianal plane only and in only one or two narrow angular zones. In all other angular zones and in the tangential directions, performance is two to five times better than the worse case value. Considering this, a "not to be exceeded" blur specification of 20µ would probably assure that 90-98% of all measurements in the image plane are better than 10µ. Even at the worse case points, modulation would be between 50 and 85% (a creditable value in the radial directions), while tangential measurements at the same point will yield modulations in the 85-95% range or better.

This rationale was utilized to justify a 20µ blur specification in initial design efforts. Work has continued in this area throughout the entire contract. This work will be discussed later in Sections 4 and 6.

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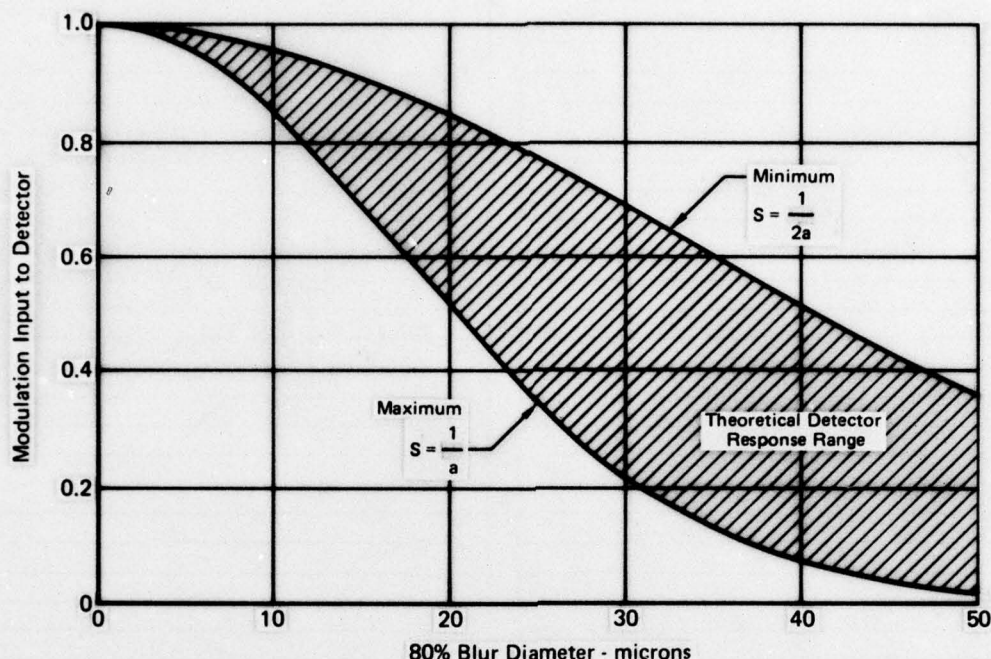
Figure 10   Modulation at Lens Image for Critical Detector Response Frequencies
(a = 0.0305mm)

3. Optical Materials

Materials considered vary from the complete family of optical glasses to optically and mechanically acceptable plastics. These tradeoffs apply primarily to the aspheric elements because the small spherical elements can be fabricated more cheaply from glass (Reference 1). In addition, the wide range of dispersions and indices of refraction available in glasses assists chromatization of a lens using plastic aspherics. Some additional materials considerations are discussed below.

o Glass Elements - Glass types for the elements, after their approximate index and dispersions are established, are then specifically selected for their physical and chemical properties. High resistance to straining and climatic variations, internal transmittance, and good optical properties are considered when identifying specific glass types.

o Plastic Elements - A detailed analysis for the specific fabrication approach of the plastic spline elements has not been made. General fabrication approaches for plastic elements are as follows:

Plastic elements can either be fabricated by casting, molding, or machining.

a. Casting is normally reserved for large (in volume and size) elements. Environmental conditions for the curing area are important, and through-put is low due to long cueing time. Fabrication rate can be increased with additional molds.

62728

b. Injection and compression are the methods used in the molding process.
    For compression molding, the plastic is in powder or pellet form
    placed between heated dies in a press. Cycle time in the press is
    relatively long coupled to in-die curing time after removal from the
    press. Injection molding uses the plastic in liquid form injected
    under high pressure into a mold. Cycle time is relatively short.
    Satisfactory injection molding of large elements is somewhat difficult
    to achieve.

c. Machining of plastic elements is an easy process through use of
    numerically controlled machines. Polishing of the elements is more
    difficult than with glass. There really is no advantage to plastic
    elements when the machining process is used.

The major advantage in utilizing plastic is in the ability to produce low
cost replications from an expensive aspheric mold. For spherical shapes,
large production runs have to be made before the cost of the plastic
elements are below their equivalent glass types.

To achieve reasonable performance levels, detailed attention has to be
given to the thermal and physical properties. Index variations with
temperature of 0.0001/deg C is one to two orders of magnitude greater than
glass. Compensation techniques through thermal sensitive spacers within
the lens mount are required.

The physical properties such as shrinkage and stability have to be
considered when selecting specific plastic types for the elements.

Anti-reflection coatings can easily be applied with some care, although
the coatings are soft as opposed to the hard coatings available on glass.

o Cost Considerations - The anticipated number of lenses required will
   dictate the approach of using all glass elements as opposed to a hybrid
   plastic and glass combination system. The cost of molds and molding
   process will have to be traded off with glass fabrication costs versus
   number of lenses required. Fabrication of spherical glass elements can
   be accomplished at relatively high volumes before a savings through using
   spherical plastic elements is realized (Reference 1).

C. PRACTICAL DESIGN CONSTRAINTS

1. Element Shape

The foveal lens achieves its imaging characteristics through the use of
unconventional aspheric spline elements. The spline elements, which have rota-
tional symmetry, cannot be generated by "standard" optical shop techniques.
The extreme asphericity dictates the use of tape or pantagraph type controlled
grinding machines. Conformance to required surface figure has to then be
established by physical profile measurements. The smaller the element diameter,
the tighter the tolerance requirements. This makes both fabrication and measure-
ment more difficult.

62728

2. Element Sizing

For the miniaturization of the original foveal lens, problems encountered during the fabrication of the "full scale" lens determined some of the basic size constraints for the study. Performance data from the first foveal lens indicated that the design could be scaled to one-half size while still maintaining adequate resolution or acuity. This proved not feasible due to the difficulties encountered while trying to grind and polish the last element ahead of the image plane. This element (number eight) has a spline/convex shape and would have a diameter of only 0.35 inch. In our existing lens this element has a diameter of 0.7 inch. Even this size was found to be marginal for generation on a tape controlled machine; therefore, the fabricator elected to hand figure the element. As a result, the measurements show that the two elements (for our two lenses) are different from each other though still within stipulated fabrication tolerances. The tighter tolerances required of smaller elements would definitely be impossible to achieve.

Subsequent discussions with the fabricator have resulted in an opinion that spline elements in the 0.7 inch diameter area or larger can be generated without resorting to hand figuring. This is also believed to be a reasonable limit for plastic elements because mold fabrication has identical problems.

Based on these points, the minimum size for any spline elements was limited to 0.7 inch. This inherently establishes a minimum focal length for the basic foveal lens of about 2 inches. A 2/1 optical relay will, therefore, be required to achieve the required effective focal length of 1 inch.

17

Section IV

SYSTEMS PERFORMANCE ANALYSIS

As mentioned previously, a systems analysis effort was run concurrent with the optical design effort in order to verify or modify lens quality requirements. This effort is described below. The non-linear nature of the RVS video requires caution in application of conventional sensor performance modeling theory. The measure of merit of the RVS as a sensor is how well its display output, presented to the observer, is a true representation of its optical input. Since the RVS is a unity magnification device, objects are presented to the observer in the same angular perspective that they are received by the sensor. With angular subtence of objects guaranteed by the inherent geometry of the RVS, degradations will appear only as contrast or modulation losses in the displayed image. This measure of merit can be obtained by the Modulation Transfer Function (MTF) of the RVS system. Figure 11 shows significant MTF's that are involved in the RVS system. This representation is somewhat different from conventional TV systems in the non-linearity at input and output ends of the system, i.e., the distortion function, $F(\theta)$, representing the focal length change as a function of the object field angle, θ.

$$\tau(S) = \frac{M_o(S)}{M_i(S)} = \tau_1(S)\,\tau_2(S)\,\tau_3(S)\,\tau_4(S)\,\tau_5(S)\,\tau_6(S) = \frac{M_o\left(\frac{1}{\phi F(\theta)}\right)}{M_i\left(\frac{1}{\phi F(\theta)}\right)}$$
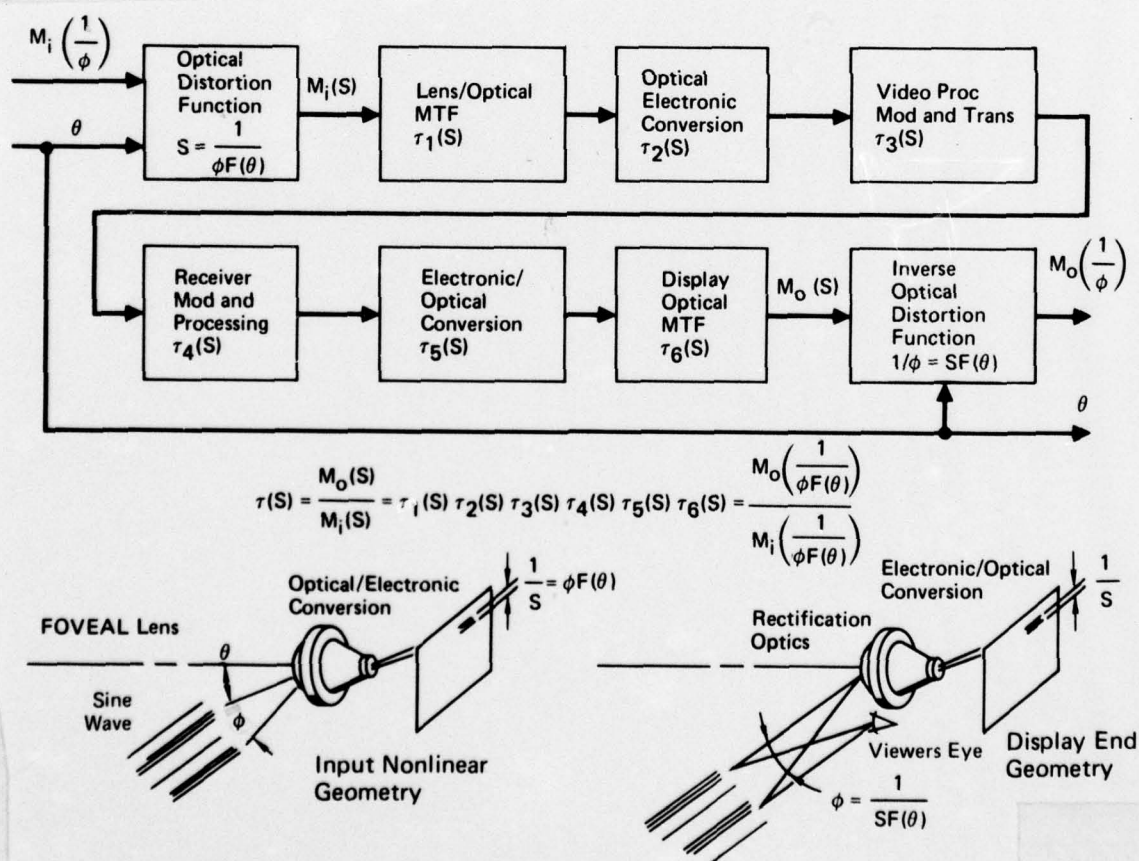
Figure 11   General RVS Optical Transfer Function Representation

18

A. THE SENSOR LENS

At the input end, the foveal or non-linear lens has the function of converting object angles, ϕ, to a linear focal plane through its focal length function, $F(\theta)$. On Figure 11 a sinusoidal object distortion is shown with angular subtense, ϕ, for one cycle. This is related to conventional spatial frequency in the focal plane by the apparent lens focal length, $F(\theta)$, i.e.,

$$S = \frac{1}{\phi F(\theta)} \qquad \text{cycles/inch or cycles/mm} \atop \text{(depending on } F(\theta) \text{ units)} \qquad \qquad \text{Eq.(11)}$$

Note that the translation from ϕ to S will vary with the angular separation the object appears from the lens optical axis, θ. Progressing to the next element of Figure 11, $\tau_1(S)$ yields modulation loss caused by the lens. Since the lens is designed with constant resolution in its focal plane, its MTF in spatial frequency, S, terms will be independent of object angle, θ. The same is true of all other elements in the MTF chain up to final object being viewed by the observer. Here the translation into angular space is the reverse of the input end, i.e.,

$$\phi = \frac{1}{S\ F(\theta)} \qquad \qquad \text{Eq.(12)}$$

Since the overall MTF, $\tau(S)$, is independent of θ, it will yield system degradation for any field angle. This is a very significant observation in that, once the system MTF, $\tau(S)$, is determined, system performance at any field angle, θ, can be instantly and simply determined through the distortion function, $F(\theta)$. It is only when relating to ground objects or to the observer that this non-linear relationship must be employed. For example, to determine system performance of a ground target having spatial frequency K at range R and at field angle θ, ϕ is simply determined as

$$\phi = \frac{1}{KR}\ .$$

This is then converted to S by

$$S = \frac{1}{\phi\ F(\theta)} = \frac{KR}{F(\theta)} \qquad \qquad \text{Eq.(13)}$$

The modulation of this object, as seen by the observer, is simply the received modulation (the target/background modulation degraded by the atmosphere) times the MTF at spatial frequency, S, i.e.,

$$M_o = \tau(S)\ M_1 \qquad \qquad \text{Eq.(14)}$$

The observer's capability to see this object, however, is a complex subject that will be addressed after system MTF's are fully defined. Starting from the sensor optical input, the optical distortion function is $F(\theta)$ as discussed in Section 3.1 and shown on Figure 3. Approximate equations are:

$$F(\theta) = F(0) \qquad \qquad \text{for } 0 < \theta < .515$$

$$F(\theta) = .755\ F(\theta)\ \theta^{-.423} \qquad \text{for } .515 < \theta < 15$$

$$F(\theta) = 10.27\ F(\theta)\ \theta^{-1.387} \qquad \text{for } 15 < \theta < 90°$$

19   62728

With F(θ) defined, the next function on Figure 11 is the lens MTF. This can be easily derived from lens design requirements. These are in terms of point spread functions at its focal plane, and the same value applies anywhere on the image area. The worst case MTF can be obtained by taking the Fourier transform of the specified worst case spread function as previously discussed in Section 3.2 and is defined by Equation (8), i.e.,

$$\tau_1(S) = e^{-1.532\, D_{80}^2\, S^2}$$

B. THE OPTICAL/ELECTRONIC CONVERSION

Based on USAF recommendations, we utilized the RCA SID 51232 as the conversion device for our model. Initially, we utilized their brochure "typical" MTF as $\tau_2(S)$. We later became concerned as to the statistical predictability of this MTF and conducted our own analysis to determine theoretical limits and statistical distribution of this type discrete image extraction system. The analysis is summarized below. Details of the analysis is presented in Reference 2.

Our reasons for concern can be shown through several simple figures. Figure 12 shows basic elements needed to study the problem. Here the scene is imaged on the array of discrete detector elements at the lens image plane. Since each detector generates an electrical output proportional to the energy it receives, the array output is essentially a sample data system as shown in Figure 13. When working with MTF theory, we are concerned with relative outputs of the elements when imaging a sinusoidal pattern. This geometry is shown in Figure 14. The problem with this type imaging system is shown in Figure 15. Here a sine wave with a spatial half period equal to the element spacing is shown in two phase positions.
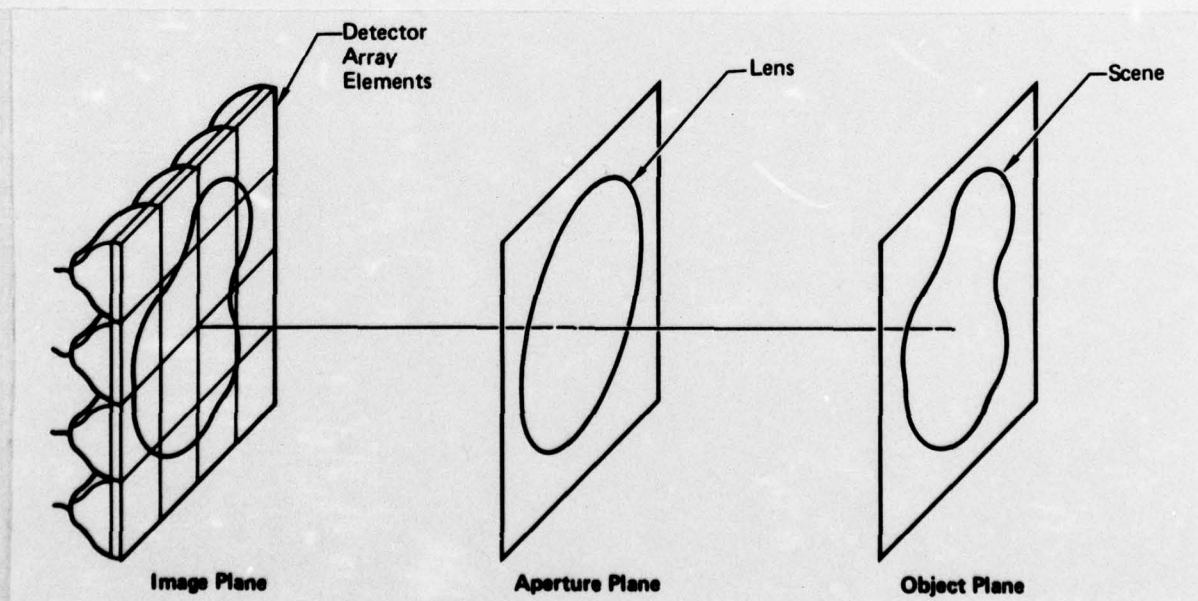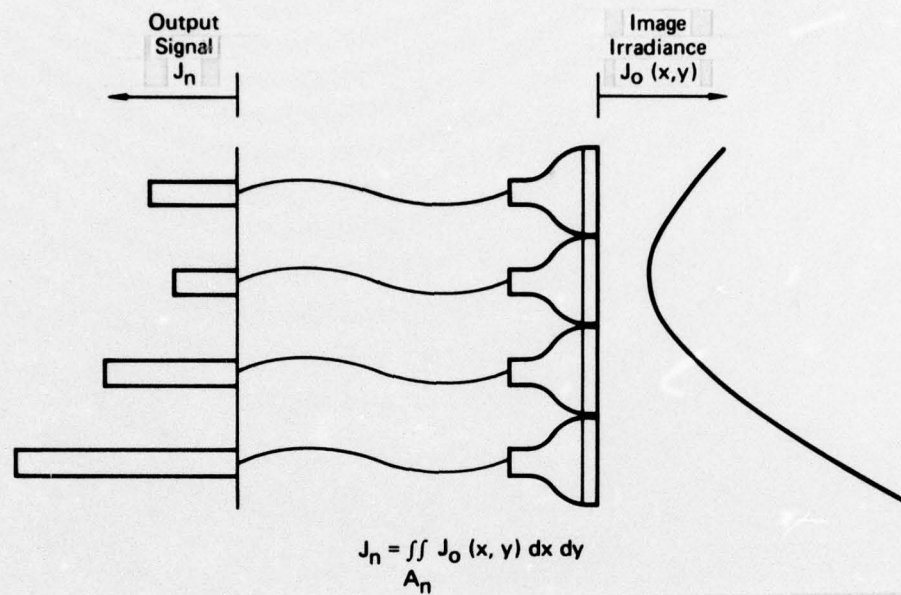

Figure 12 Array Detector Geometry

20

Output
Signal
J_n

Image
Irradiance
$J_O(x,y)$

$$J_n = \iint_{A_n} J_O(x,y)\, dx\, dy$$

Figure 13 Input/Output of Array Elements

$$\text{Modulation} = \frac{J_{max} - J_{min}}{J_{max} + J_{min}}$$

Image
Irradiance

Output
Signal

J_{max}

J_{min}

Modulation = M
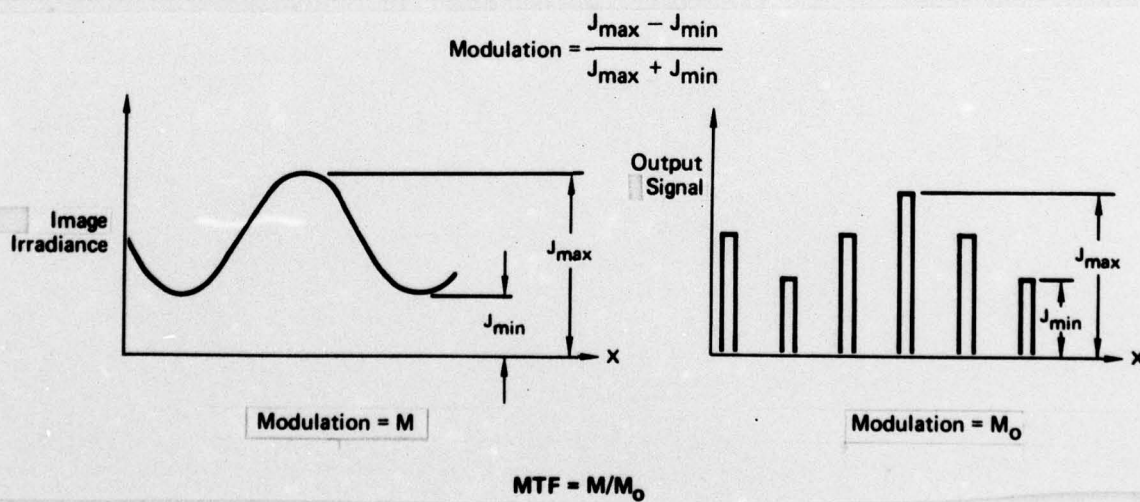
J_{max}

J_{min}

Modulation = M_O

$$\text{MTF} = M/M_O$$

Figure 14   Modulation and the Modulation Transfer Function (MTF)
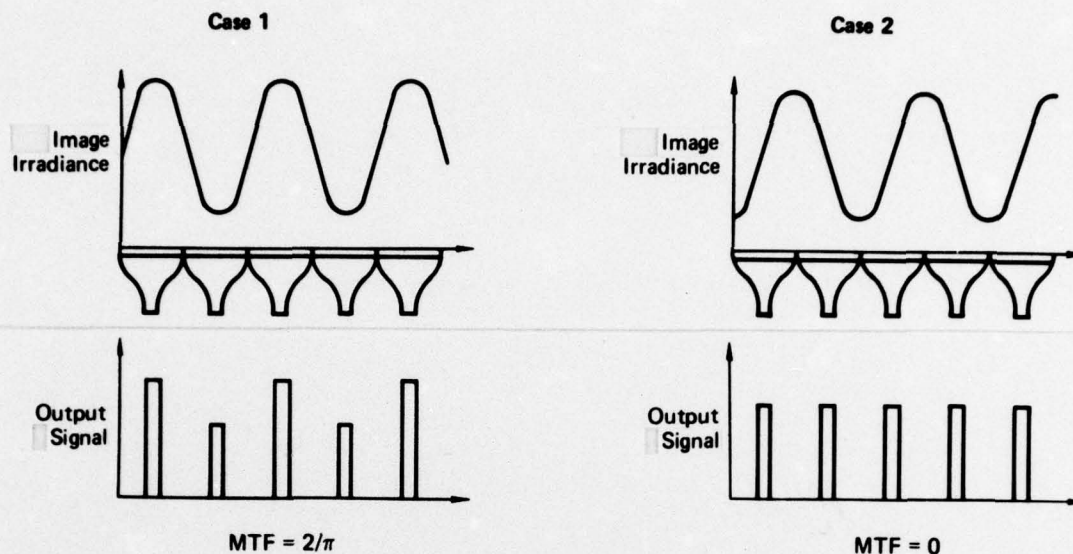
21

Figure 15 Variation of MTF with Phase Angle

In Case 1 a large modulation in electrical output is obtained, while in Case 2 no output is produced. Obviously, this phase should be handled as a random input variable, and our primary interest is in the statistics of the output modulation. This theory is developed in Reference 2. A sample of the kinds of data derived for the RCA array in that reference is shown in Figure 16. This is the probability density distribution of modulation at two different spatial frequencies. Note that discrete maximum and minimum limits exist. This is true of all spatial frequencies as shown on Figure 17. Here the maximum, minimum, and average modulations at all spatial frequencies are shown. In practice, the actual MTF can be anywhere between these limits.

It is interesting to compare these statistically derived data to the conventional method for handling discrete detectors - the Fourier transform of a square spread function. This comparison is made on Figure 18. Note that the conventional method of representing an array MTF is considerably optimistic, i.e., a very low probability exists that it could be realized. The average theoretical MTF was selected for our systems analysis. This is the mean MTF, which will be exceeded approximately 50% of the time.

C. REMAINING MTF'S τ_3 TO τ_6

The remaining MTF's of Figure 11 are impossible to define at this time. However, the following rationale was used to make preliminary analysis possible.

o No video processing is assumed, and no degradations due to modulation, transmission, reception, and demodulation are assumed. This implies τ_3 and $\tau_4 = 1$.

o It is assumed that display resolution performance far exceeds the requirements so that τ_5 and $\tau_6 = 1$ over the spatial frequency range of interest. Since size/space and cost requirements are not very stringent for the remote display, this seems like a reasonable assumption at this point.
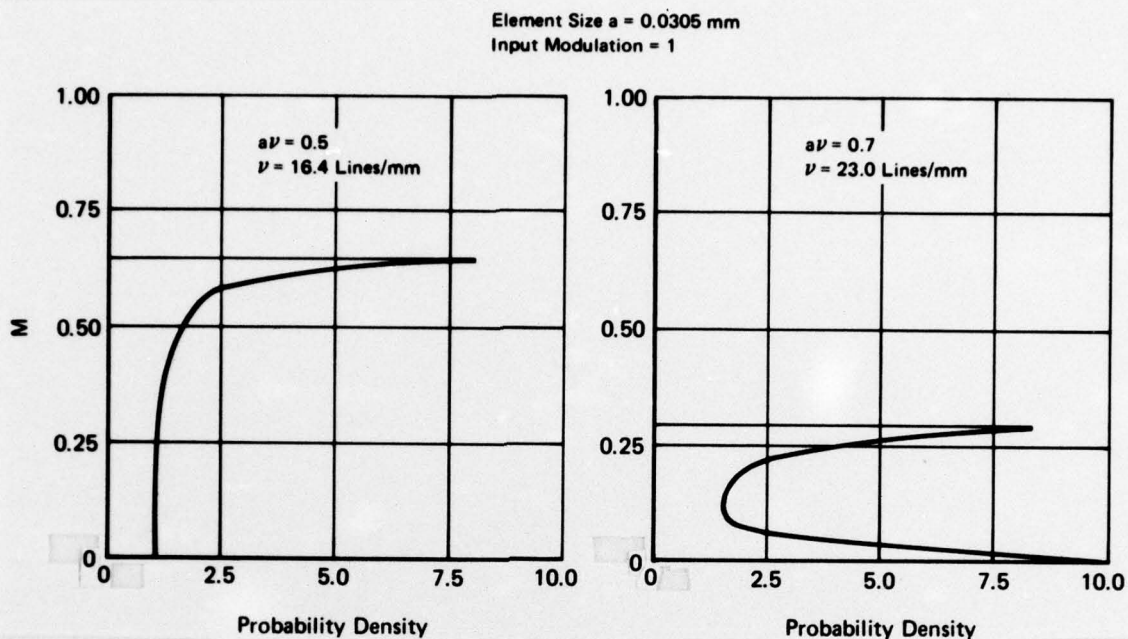
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62728

Element Size a = 0.0305 mm
Input Modulation = 1

Figure 16 Probability Density Function of Modulation - RCA SID 51232
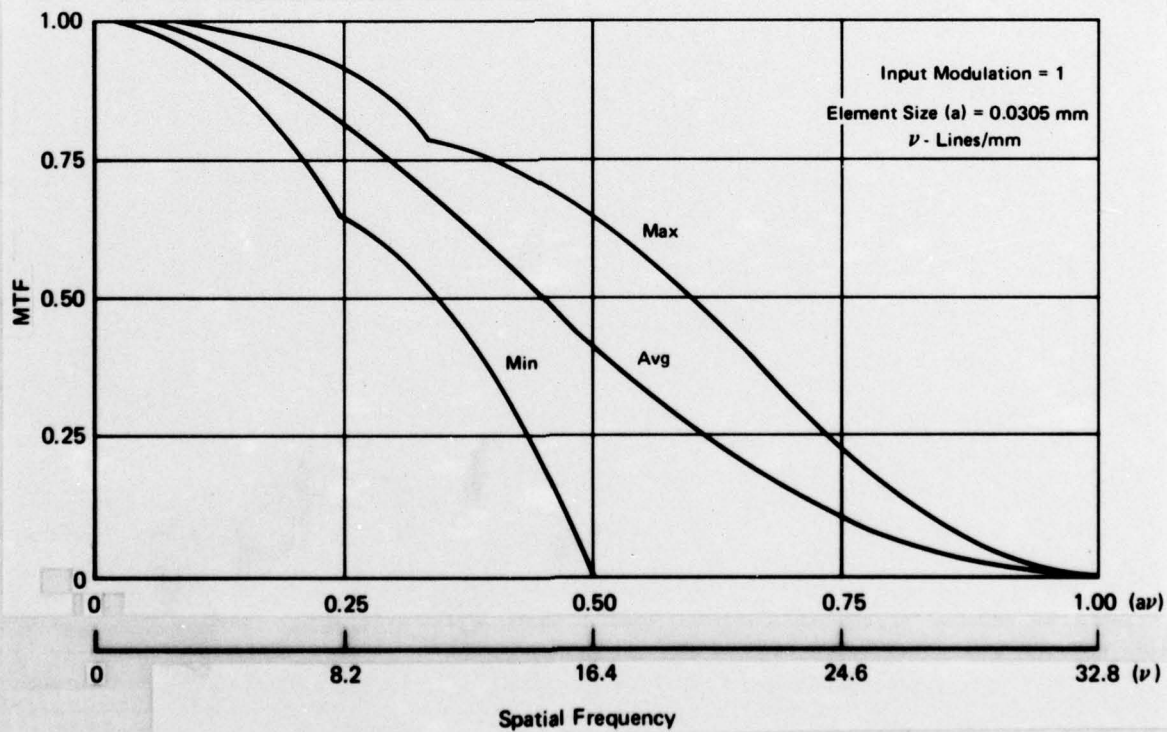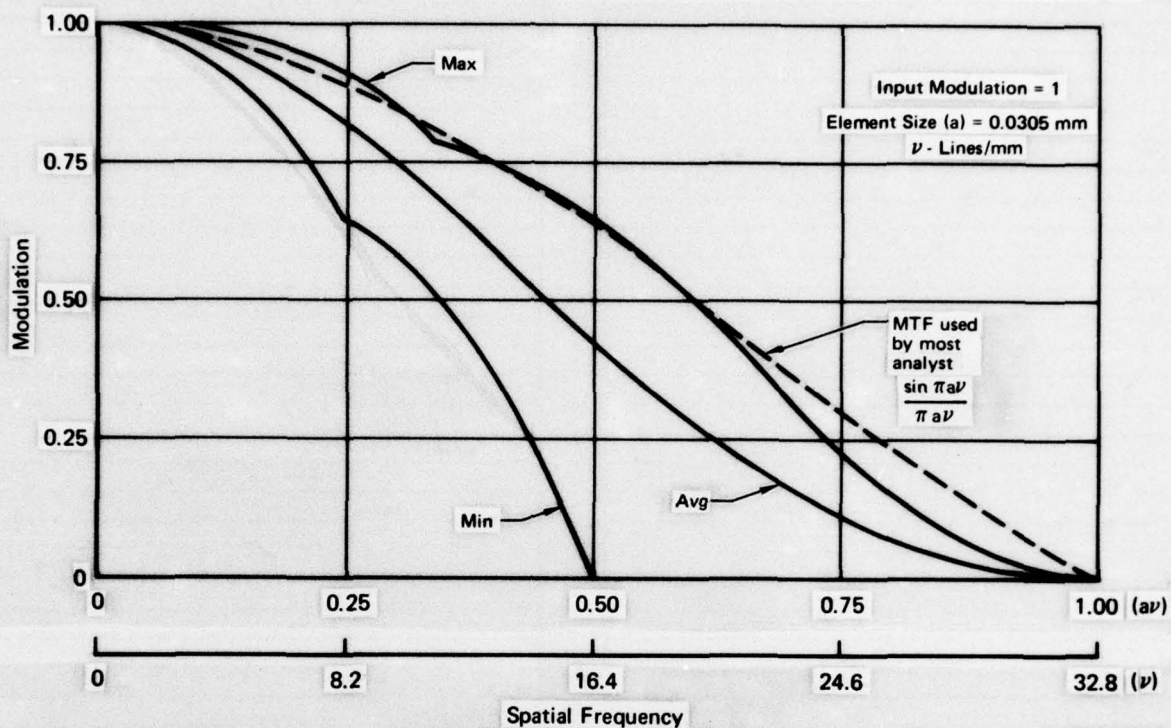

Figure 17 Maximum, Minimum, and Average MTF - RCA SID 51232

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**Figure 18   Theoretical MTF Compared to Conventional Representation Method
RCA SID 51232**

Utilizing the parameters defined above, the overall MTF is:

$$\tau(S) = \tau_1(S)\tau_2(S)$$

This function describes the modulation loss in the final displayed image to the viewer. If the viewer is to resolve this displayed image, it must have sufficient angular subtense, contrast, brightness, and signal to noise ratio. The first of these can be determined from spatial frequency, S, and the lens distortion function, $F(\theta)$, i.e.,

$$\phi = \frac{1}{S\ F(\theta)} \cdot$$

Contrast is available from the MTF, i.e.,

$$M_o = M_i \tau(S).$$

Brightness is a characteristic of display capability; it was carried as a variable in the analysis. The RMS noise in the displayed image arises primarily from system electronic noise and sensor CCD element non-uniformity. A value of 0.4% was extracted from RCA data on the CCD.

62728

D. OBSERVER PERFORMANCE

Observer capability in terms of the above parameters was derived from the Statistical Detection Theory developed by H. A. Ory of Rand Corporation (Reference 2). In this document, statistical detection theory of threshold visual performance is developed in which the neural excitation noise results from both target and background luminance. Detection occurs if the number of excitations resulting from observation of the fluctuating target and background luminance exceeds programmed decision criterion. This work was developed for detection of a blob from a uniform background and was verified by the Tiffany data on visual thresholds. It must be modified substantially for the sinusoidal target of MTF theory. This is accomplished as derived in the work of Reference 2. The resulting equation is plotted in Figure 19 for three levels of display brightness. Note the trends are correct and magnitudes close to what experience would dictate. The penalties of low display brightness are clearly seen. For example, if M_o is about .0125, 2.5 min arc resolution can be obtained from a 10 ft-lambert display; while only about 12 min arc could be obtained from a 1 ft-lambert display.

System noise was included by computing the rms of the visual threshold functions with system rms noise. A noise value of .004 was used for this purpose.
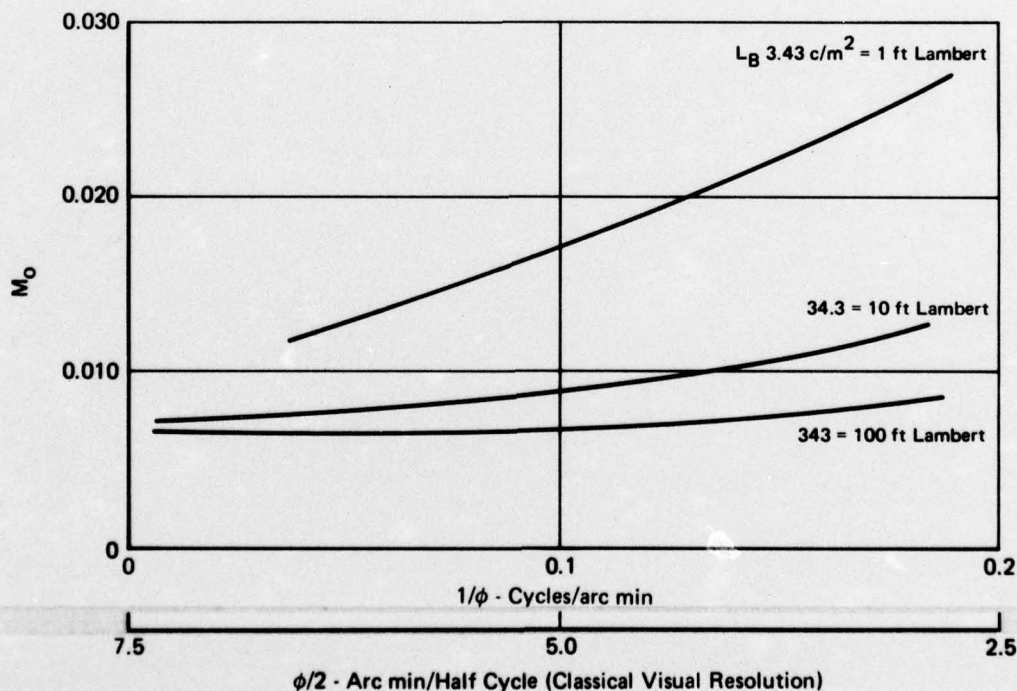

Figure 19   Visual Threshold as Functions of Display Brightness and Resolution

E. RESULTS

Using the analytic model discussed above, the effects of lens optical quality was examined for several levels of display brightness. Figure 20 shows results for two levels of display brightness – 100 ft-lamberts and 1 ft-lambert. By locating the spatial detail of interest on the x-axis, the sensor input modulation or contrast required for detection of this detail is read from the y-axis. The following conclusions can be reached from this figure.

o The 20μ lens quality estimated early in the study was a good choice. Improving quality to 10μ buys very little improvement, while reducing quality to 40μ causes significant degradation at low contrast. In addition, a 40μ lens could not support either image magnification or a better CCD if these features were required in the future.

o Good display brightness is even more important than lens quality in achieving good performance.
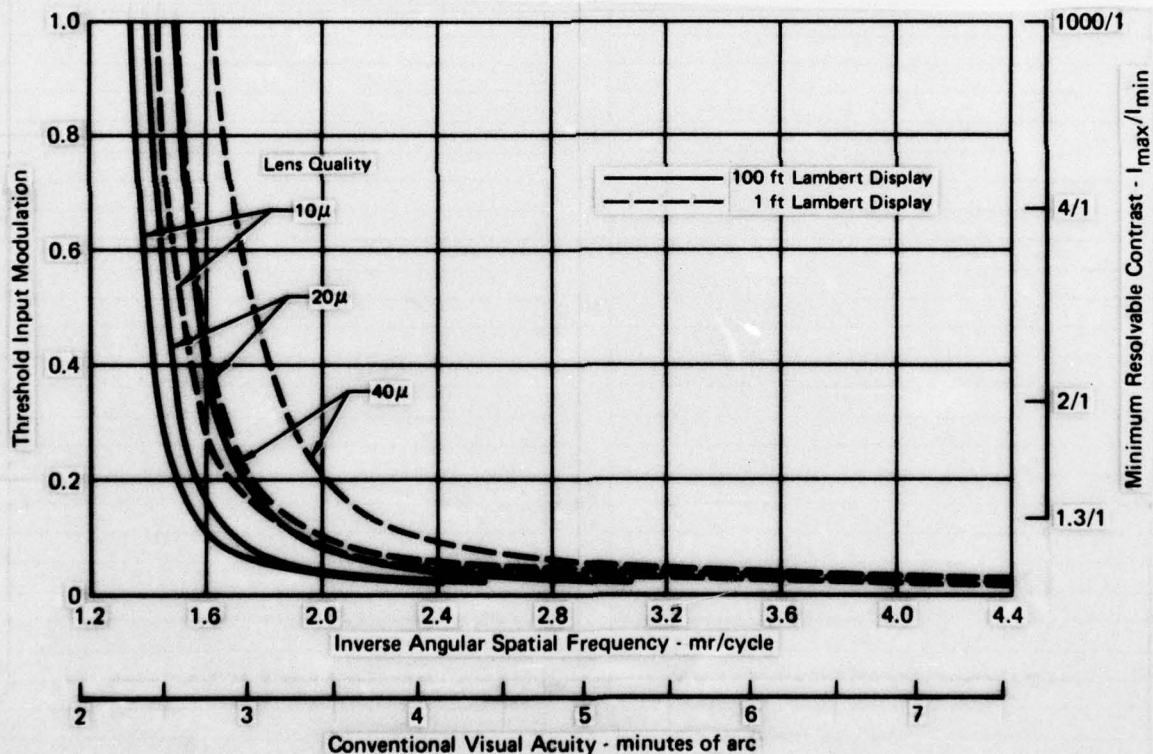
Figure 20   Minimum Resolvable Contrast - 1 In. Focal Length Lens, RCA SID 51232 Sensor

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Section V

OPTICAL DESIGN STUDIES

Before beginning detailed discussions of this phase of the effort, some reiteration of certain input data is in order. First, a constraint of 2 inch minimum focal length is required of all foveal lens configurations for reasons discussed in Section 3.3. Therefore, a 2/1 optical relay will be required to achieve the desired 1 inch effective focal length. Design feasibility of this relay is also considered part of the optical design studies presented in this section.

The work described in this section proceeds along the lines of Figure 21. This is a repeat of the lower portion of Figure 1 with the addition of "sample configuration" identification letters. These sample configurations represent significant stages in the several hundred individual computer runs that were made during the study. These selected examples are fully identified in Table 1. Reference to this table and Figure 21 will be of assistance in the following discussions.

To give the reader an appreciation for the volume of data generated during this study, one computer run has been reduced and is enclosed as Appendix A.
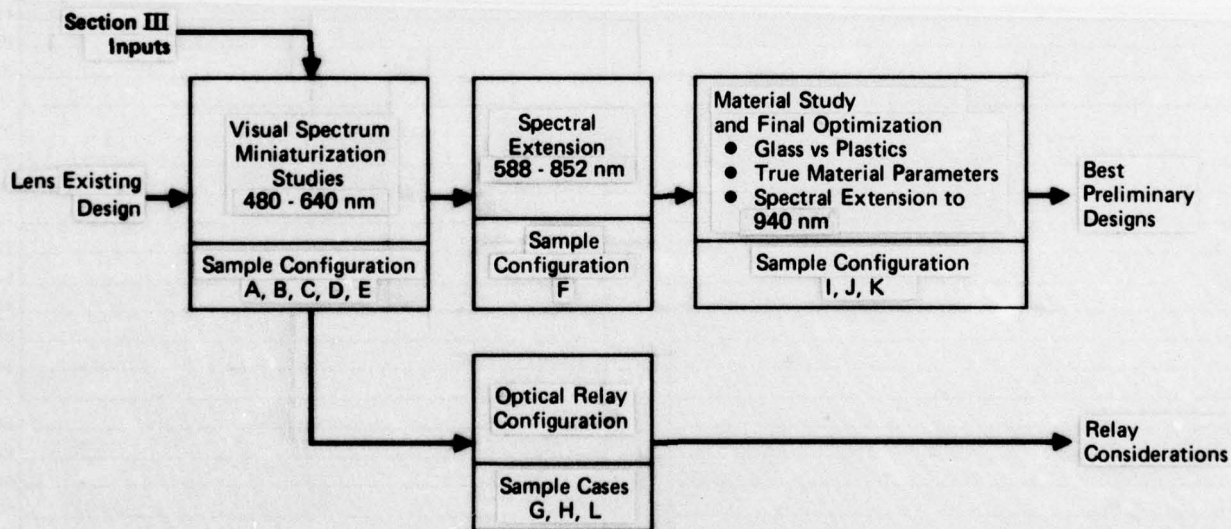
Figure 21 Design Study Approach

A. MINIATURIZATION IN THE VISUAL SPECTRUM

The optimization process started with the original foveal lens, Optical Configuration (A), on Table 1. For the initial study sequence, the same spectral band (480 nm to 640 nm) and materials (SK 16 and F2) were utilized, and the first element and pupil diameters were reduced by 50%. The rescaling of the original design was basically a manual operation involving multiplication of the numerical aperture, spline endpoint heights, axial separations, and associated boundary

Table I Run Description

Design Run Identification Letter	Title	Aperture Ratio		Axial Focal Length (in.)	First Element Diameter (in.)	Entrance Pupil Diameter (in.)	Spectral Range (nm)	Field-of-View (deg)	Material
		Basic	With Relay						
A	33CD Original Foveal Lens Design	5.6	2.8	2	8	0.360	480-640	160	Glass F2 & SK16
B	08 Front Triplet Half Size	11	5.6	2	4	0.180	480-640	160	Glass F2 & SK16
C	10B Front Triplet Half Size	6	3	2	4	0.324	480-640	160	Glass F2 & SK16
D	10BD Front Triplet Half Size 0.0675 Pupil	7.4	3.7	2	4	0.270	480-640	160	Glass F2 & SK16
E	13A Four in., Conf 50.8 Alternate Variables	12	6	2	2	0.162	480-640	160	Glass F2 & SK16
F	17 Front Triplet Half Size 0.59 to 0.85	6	3	2	4	0.324	588-852	160	Theoretical Glass
G	09 Double Gauss Relay	3	NA	2:1 Conjugates	NA	NA	480-640	160	Glass LAK N12, SK51, SSK4, SF7, F8
H	25 Front Triplet Half Size Spline Field Lens	6	3	2	4	0.324	480-640	NA	Glass F2, SK16, SF-15, LAK 3
I	23 Front Triplet Half Size IR Materials Change FOV = 60	6	3	2	4	0.324	588-852	120	Glass/Plastic SF19/Acrylic, SK16/Styrene
J	20 Front Triplet Half Size 0.59 to 0.94	6	3	2	4	0.324	588-852	160	F2, SK16, SF52
K	20A Front Triplet Half Size 0.59 to 0.94	6	3	2	4	0.324	588-940	160	F2, SK16, SF52
L(G+H)	25A Front Triplet Half Size with Relay	6	3	1	4	0.324	480-640	160	G + H

limits by the scale factor and multiplication of curvatures by the reciprocal of the scale factor. Only the front triplet portion of the foveal lens was rescaled. The triplet diameter is controlled by boundary limits, which are tied to the numerical aperture. The optimization program automatically scales input prescriptions to unit focal length. When scaling, the optimization program does not correctly compute the spline values. Therefore, to prevent automatic rescaling from occurring, the curvature of the surface preceeding the aperture stop was manually changed to bring the paraxial marginal ray through the stop at the same slope as in the original design thereby providing an input prescription, which has been manually set to unit focal length. The rescaled design was then optimized using damped least squares followed by an orthonormal optimization mode. The meridianal ray intercepts of the new design, B, were then compared with A scaled to the same focal length on Figure 22. Note that blur diameters are essentially equal in either case. This is as predicted by the F/No., size, resolution parametrics of Figure 9 that were generated by geometrical optics extrapolations from our existing lens. That figure is repeated for convenience as Figure 23. The peak blurs from Figure 22 are also annotated on this figure. Note the agreement of Case B with theoretical curves. The parametrics of Figure 8 were further verified by running the lens optimization program first for a smaller F/number, while maintaining the same lens size (Run C), and then by reducing clear aperture, while maintaining F/number constant (Run E). Again, the peak blurs shown on Figure 23 were quite close to those predicted in Figure 23.

Data of Figures 22 and 23 plus the reasonable lens profiles of the best configurations shown in Figure 24 convinced us of the optimization program's validity. However, since practical considerations limit the foveal lens focal length to 2 inches (see Section 3), an optical relay is necessary to achieve correct image size. Before proceeding, we felt it best to determine the feasibility of such a relay.
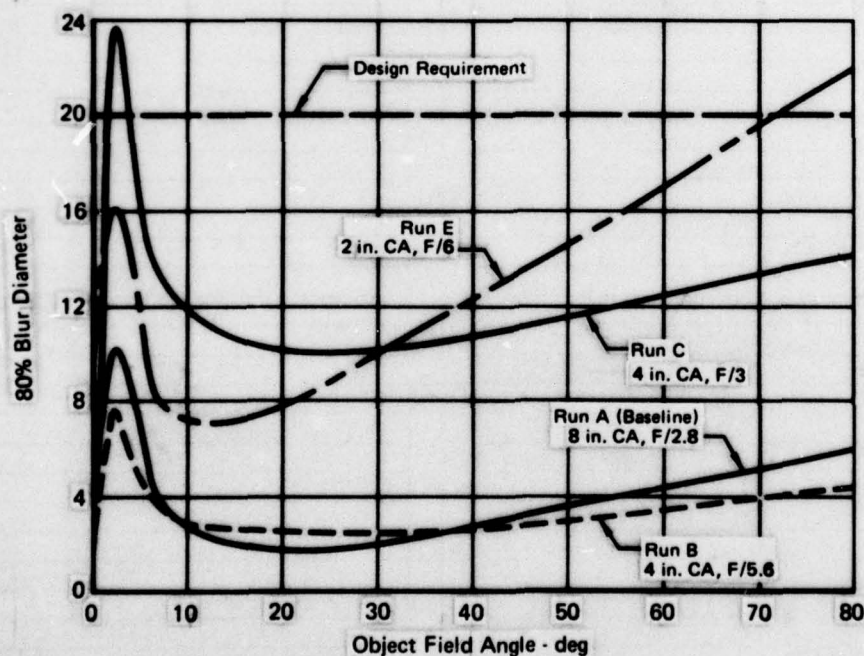

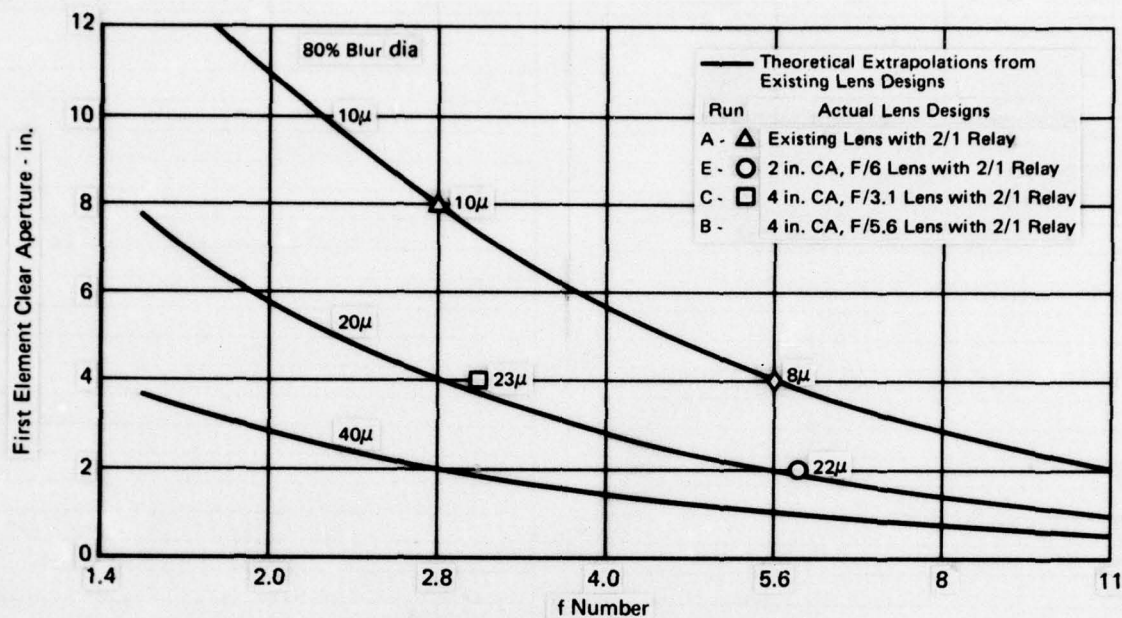Figure 22   Visual Lens Performance - 1 In. Focal Length

Figure 23 Theoretical Lens Size Parametrics
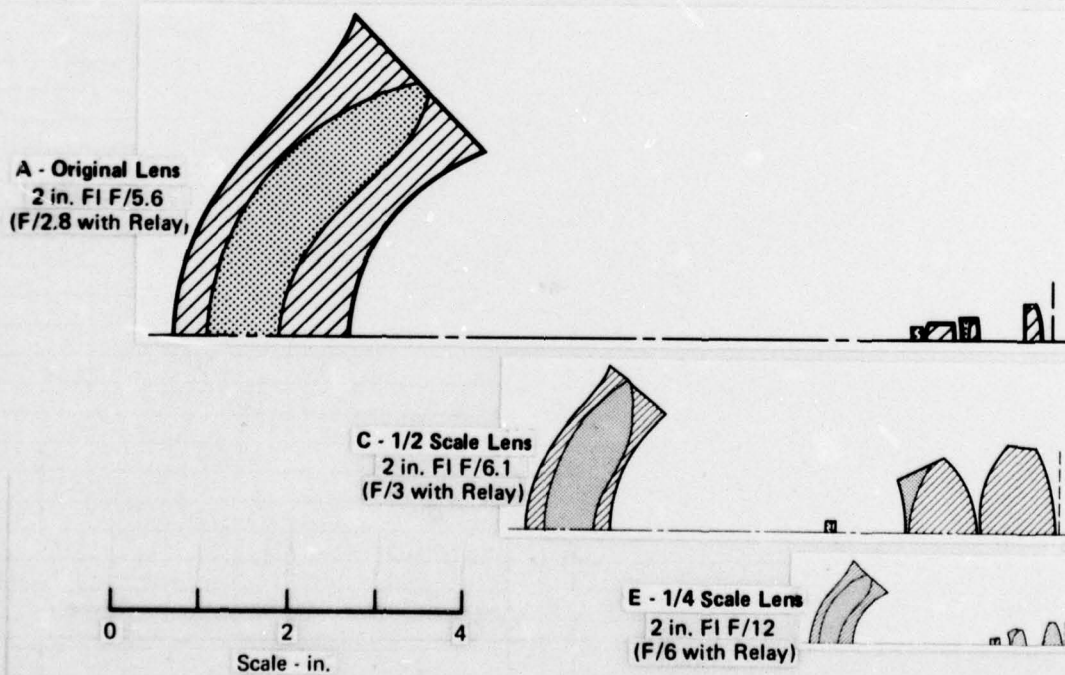Effective Focal Length = 1 In.

Figure 24 Visual Optical Designs

B. OPTICAL RELAY CONFIGURATION

Using the C design as a starting point, a look at the chief rays exiting from the foveal lens indicated the presence of considerable shift of the exit pupil image with field angle. Figure 25A is a chief ray plot from C. A spline field lens eliminates this position shift and would then permit the design of a double Gauss relay, which can operate at system aperture ratios of F/3 (Figure 25B). One alternative to a spline field lens is to stay with a conventional relay lens configuration operating at a comparative aperture ratio of F/1, which requires the use of more lens elements to obtain the same degree of image quality (Figure 25C). Another alternative would be to use an external entrance pupil relay design with a comparative aperture ratio of F/3. This is not conventional and would require additional lens elements for aberration correction (Figure 25D).

After considering the predicted complexity of the various relay options, the spline field lens approach was selected as being the lowest cost with the greatest probability of providing satisfactory image quality in a minimum package size. Another consideration in selection of the spline field lens approach for further study was that the exit pupil formed by the field lens could be used as an aperture stop in the system more conveniently than the stop location inside the existing foveal lens design.

The spline field lens was manually configured to form a stationary exit pupil image for five off-axis field angles (2-1/2, 7-1/2, 20, 40, and 80 degrees). One spline segment was used for each angle making the field lens a five spline surface (the special surfaces in the foveal lens are defined by four splines each). After manually configuring the field lens, the foveal lens system, including the field lens, was optimized using the automatic design program resulting in design H. Performance of this configuration is shown on Figure 26. In parallel with this portion of the study, a double Gauss relay was optimized, G, at 2:1 conjugates using the image size of the foveal lens as an object and using the foveal lens exit pupil location as an object distance for the relay. The optimized relay was then added to H and performance of the resultant system, L, was computed. The performance of this combined system is also shown on Figure 26. It is clear from these data that the relay is contributing excessive degradation to image quality. It was clear from blur plots that the relay had excessive flare, i.e., the extreme marginal rays were diverging excessively. For this reason, a stop was placed in the relay to limit energy transfer to the center 50% of the ray bundles. These data, also plotted on Figure 26, show very good performance. In fact, it suggests more of the ray bundle could be utilized effectively, while still meeting design requirements.

In conclusion, the above results indicate the spline field lens is performing properly. In addition, the relay optical flare noted above is a well-known characteristic of the double Guass design, and correction of this problem is covered by many sources, e.g., Reference 4. For these reasons, we decided to
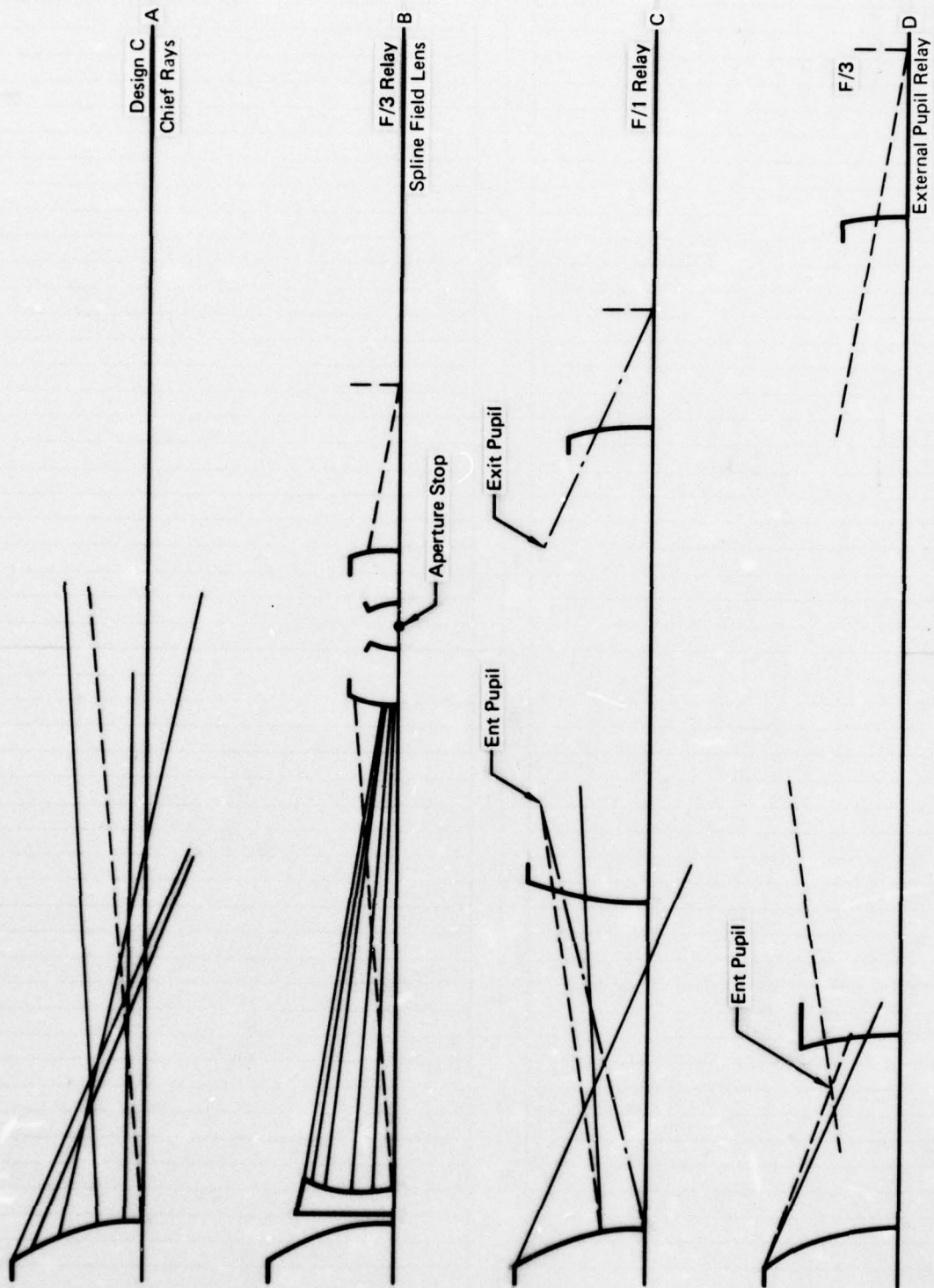
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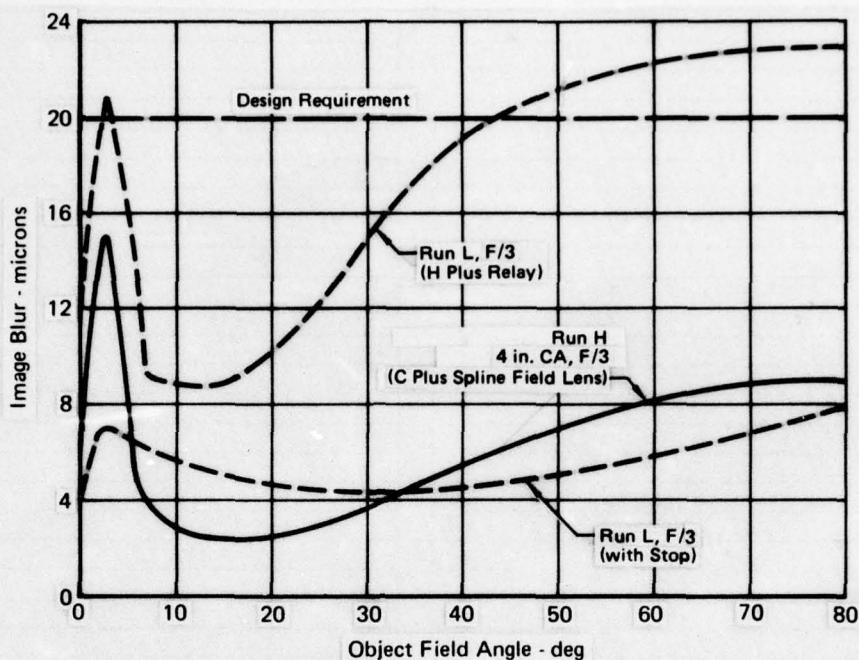Figure 25 Optical Relay Considerations

32

Figure 26   Optical Relay Performance

terminate work on the relay and concentrate on design and optimization of the basic lens. For reference, the L lens, which terminates this effort, is shown in Figure 27.

C.   EXTENSION OF SPECTRAL RESPONSE

For an analysis of spectral shift to longer wavelengths on the system performance, configuration C was taken as a starting point, and the refractive index and dispersion values for the prescription were changed to correspond to the region 588 nm to 852 nm using a mean wavelength of 687 nm. Because the mean for the visible was at 546 nm, the optimization program rescaled the focal length shift and corresponding manual changes to the splines were required. Having completed the prescription setup, the design program was utilized to optimize the resolution performance for this shifted spectral region using refractive index and dispersion of the lens elements in addition to the previously used variables. After optimizing, this configuration was designated Run F. Its performance is shown on Figure 28. The results were very encouraging - performance was better than Run C on Figure 22. Some improvement was expected from the behavior of refractive index in this spectral range compared to the visual spectral range.

It should be noted that a glass materials optical performance math model was used by the computer for this optimization; i.e., the computer uses a continuous index/dispersion function that is representative of available glasses. During the materials study and final optimization phase, actual glass types are substituted that most closely match computer selected parameters.
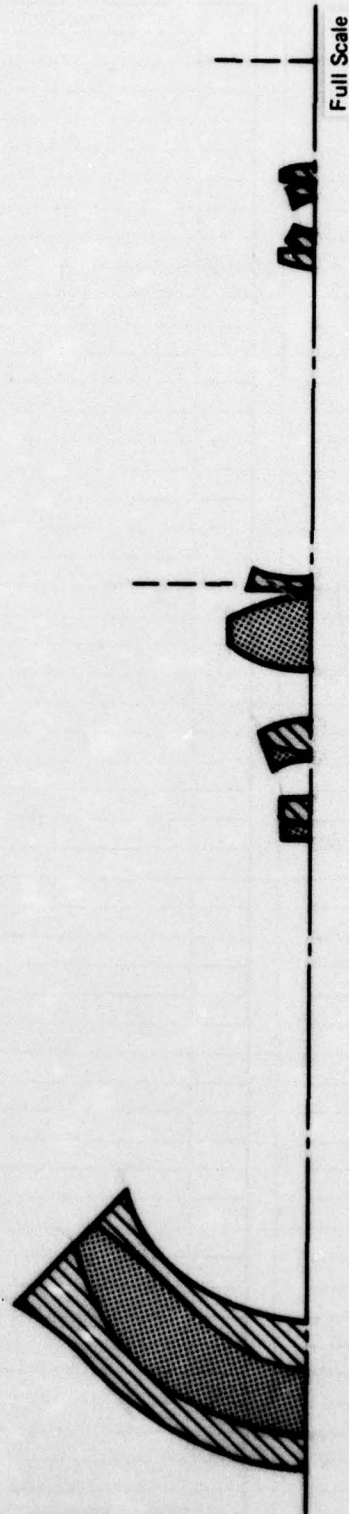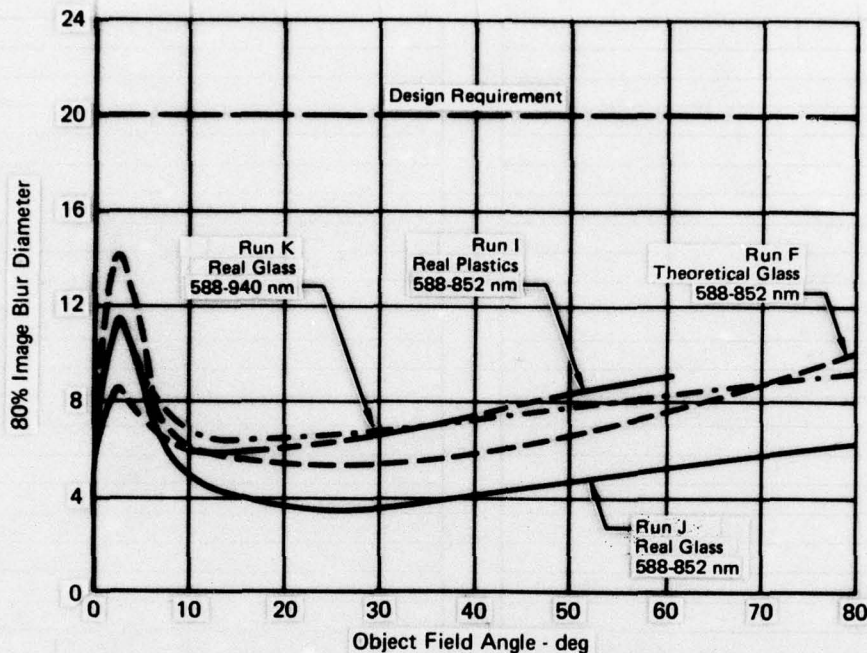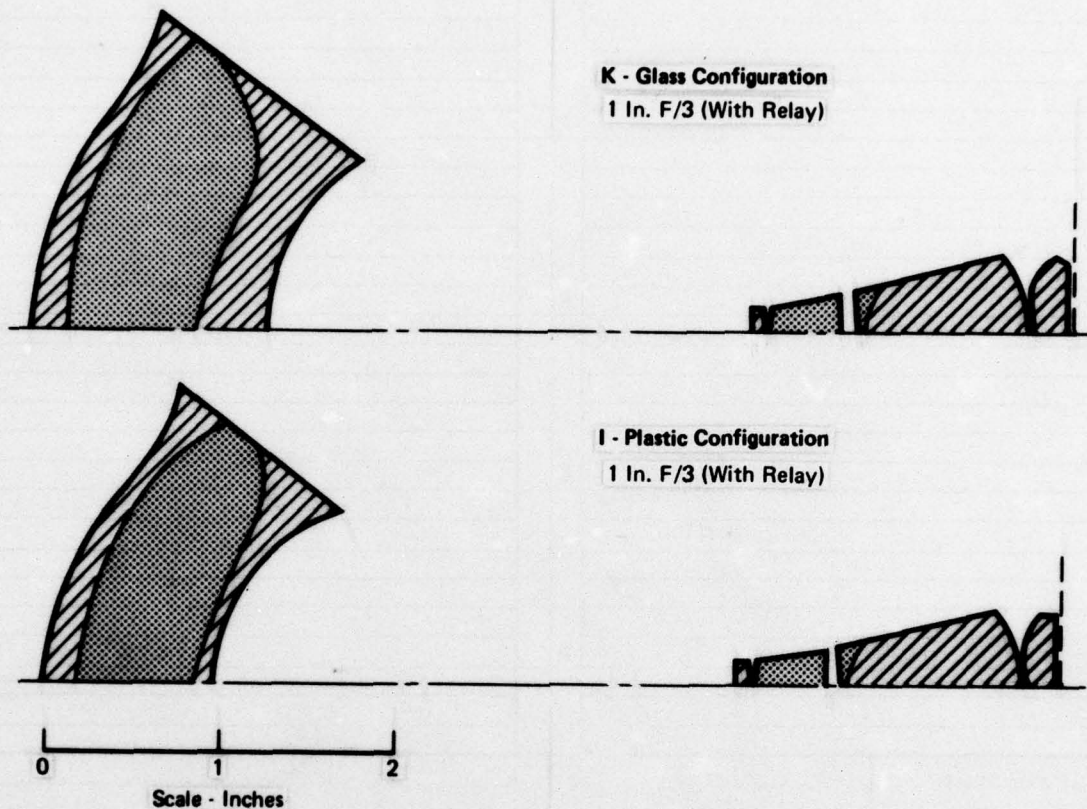
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Figure 27 Configuration L Optical Design
1 In. Focal Length F/3

Full Scale

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Figure 28   Extended Spectral Range Configurations
1 In. Effective Focal Length, F/3, 4 In. Clear Aperture

D.   MATERIALS STUDY AND FINAL OPTIMIZATION

The optimized glass IR design using theoretical glass, F, was used as a starting point for evaluation of the possibility of fabricating the spline lens elements from plastics. The mapping function for the foveal lens is primarily achieved at the first lens surface. In the glass design this surface is a spline and required a refractive index of 1.62 with an incidence angle of approximately 70° in order to obtain the required bending of the edge field chief ray. Bending of the chief rays along the same path with a representative plastic material of index 1.49 would require even steeper incidence angles, which is analogous to asking for more work from the first spline surface. A reduction of the sine of the incidence angle in proportion to the refractive index change in going from glass to plastic will keep the work load on the first surface constant, thereby making performance comparisons with the preceeding designs more valid. The change in incidence angle amounts to reducing the field of view to 120°. The result of optimizing the foveal lens with acrylic and styrene materials on the spline elements is shown as I on Figure 28. Surprisingly, performance is better than run F, the glass design. Some of this improvement (about 5%) would be expected due to effective distortion reduction caused by the smaller FOV. The remainder of this improvement may be due to a higher degree of optimization being achieved through repeated iterations and the resulting higher level of familiarity with the 4 inch clear aperture, F/3 lens configuration. This can also be seen in Run J, which is the result of replacing the theoretical glass parameters of Run F with real glass parameters for repeated computer optimization runs. Again, performance exceeds Run F, indicating a greater degree of optimization. The lens configurations of Runs I and J are shown in Figure 29.

35   6 2 7 2 8

K - Glass Configuration
1 In. F/3 (With Relay)

I - Plastic Configuration
1 In. F/3 (With Relay)

0   1   2
Scale - Inches

Figure 29 Optical Designs - Extended Spectrum

As a final step in the study, Configuration J was evaluated over the spectral range of 588-940 nm, which covers most of the sensitivity range of the proposed silicon CCD sensing array. This performance is shown as K on Figure 28. Note performance is only slightly degraded from Run J. However, performance is still twice as good as the original design specification of 20μ.

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Section VI

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

In general, results were more favorable than expected. The final optimized miniature lens design, I (plastic) and K (glass), performed approximately two times better than expected. This, in itself, raises two valid questions, which are:

o Why did the lens exceed performance estimates?

o Could the lens be made still smaller?

To examine the first question, we carefully reviewed all computer runs. A key, we believe, can be seen in Table 1. All sample configurations that agreed with our geometrical optics extrapolations from our existing lens A utilized only F/2 and SK-16 glass types. This was found to be a constraint on all these design runs. When it was removed (after case E), the performance steadily improved. This leads one to the conclusion that, very possibly, our original lens A was not completely optimized. We are presently rerunning this lens without the "glass type" constraint. While results are not available at this writing, we will continue this investigation to resolve this apparent inconsistency.

If it is true that twice the optical quality can be achieved from any foveal lens than originally anticipated, the geometrical optical predictions of Figure 9 must be revised as shown in Figure 30. Based on these curves, a 1/4 scale lens of the same F/number is feasible that still meets our original specifications. Such a lens would be similar to configuration E of Figure 24. With its relay, this lens could be packaged as shown in Figure 31. When it is compared to possible packaging of configuration K, the advantage of further miniaturization is seen to be approximately a 40% reduction in length, about 30% reduction in height, and a 50% reduction in width. Weight would be approximately 1/2 that of the larger lens.

We believe there is a very valid technical reason for staying with the larger, higher performance lens. This lies in its ability to support a higher resolution CCD or optical image magnification. Since the latter is the most stringent requirement, it was studied in detail using the systems model developed in Section 4.

Magnification is included in this model by simply changing all S values to the right of the lens/optical MTF to S/M. Results were obtained for magnifications of 2 and 4 and lens qualities (τ_1) representing 10μ and 20μ image blur values. These results are shown on Figure 32. Note that changing from a 10μ to 20μ lens quality has almost no effect at unity magnification (percentage wise); while at 2x, it lowers low contrast performance between 10 and 20%. At 4x magnifications of this degradation increase to the 30 to 40% range. The 10μ lens can easily support 4x magnification, while the 20μ lens cannot.

Added to the above concerns with the 1/4 scale lens is that of fabrication feasibility. There may be considerable technical risk in achieving the high surface slopes required for the small lens, while maintaining adequate tolerances. This, we believe, is pushing state-of-the-art in aspheric fabrication for either glass or plastics.
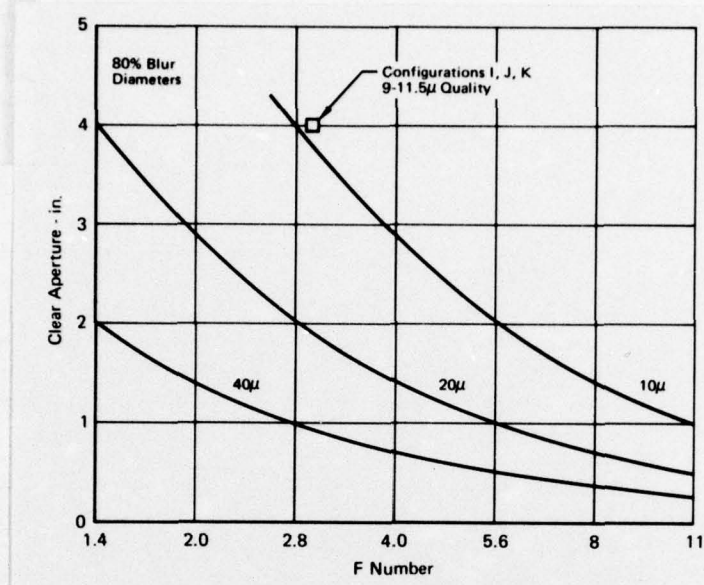
62728   95

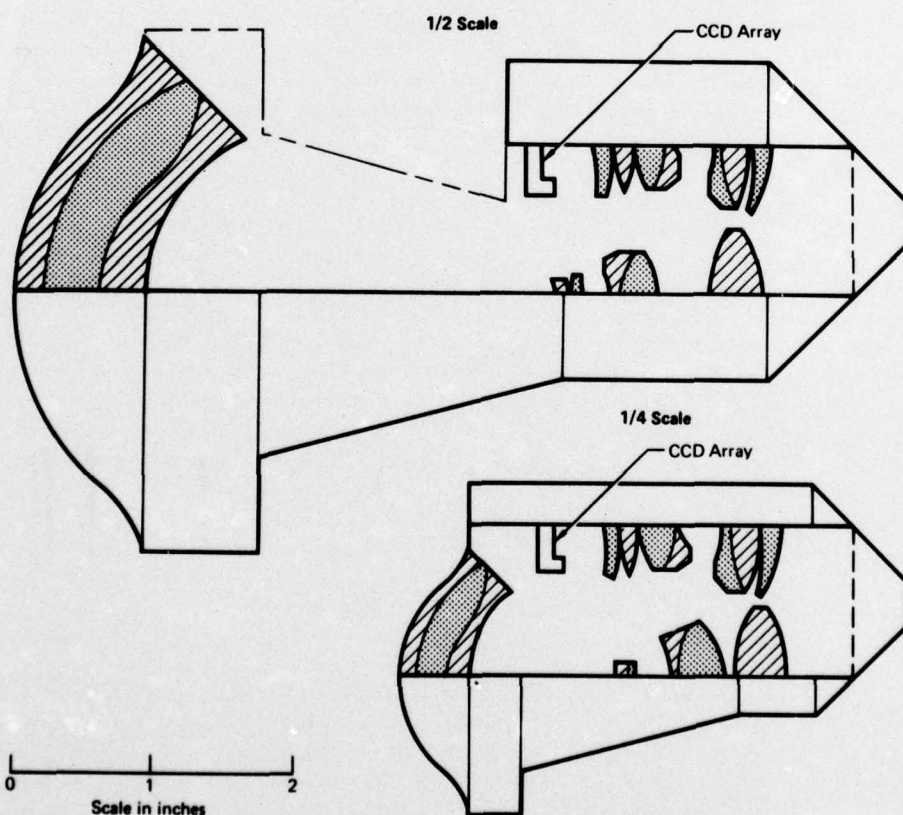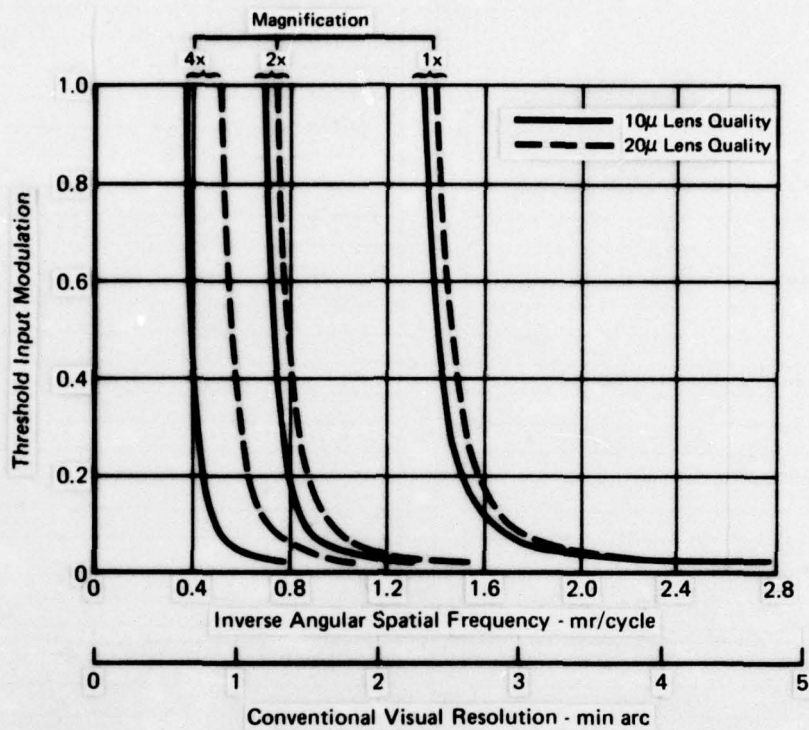**Figure 30   Revised Foveal Lens Size Parametrics**

Figure 31   Possible Lens Layouts

62728

Figure 32   Minimum Resolvable Contrast with Image Magnification
1 In. Focal Length Lens Plus RCA SID 51232 - 100 fL Display

B.   RECOMMENDATIONS

Based on concerns listed above, we recommend a half-scale lens similar to that of optical designs K or I be fabricated. We believe either is well within the state-of-the-art; however, the facts are:

o Only 120° FOV has been theoretically proven for the plastic lens compared to 160° for the glass configuration.

o Thermal problems are known to exist with the plastic lens (see Section 3). Mechanical compensation would positively be required. This would involve considerable non-recurring costs to assure maximum optical performance, mechanical rigidity, and good service life.

At this point it appears that the best approach would be to fabricate a lens of the plastic design, I, but use glass with optical characteristics identical to the plastics. This design could be prototyped and tested inexpensively. Later, as production requirements and quantities become firm, it could be converted to plastics to reduce costs.

62728

Appendix

SAMPLE LENS DESIGN COMPUTER RUN

The following pages contain a sample lens design computer run. Approximately 100 runs were required and were analyzed in order to finalize the lens prescription.

62728

95

NME,RAD,SASC,NMA
NSE(I),QAM,MN,NSA

						N1	N2	N3	N4	M1	M2	M3	M4	M5	M6	M7	MOR	
						-0	-0	-8	-0	-0	-0	-0	5	1				

62728

```
FOCUS
 0.006960 -.0075054 -.0572753 -.2304429 -.6696021-5.4634903 0.0000000
 0.0000000  0.0000000  0.0000000  0.0000000  0.0000000  0.0000000

DOLD= -4.843  1.12296E-09
 3  .40000  .97285/    .09562
 4  .39796  .72750/    .07356
 5  .39798  .69703/   .18106
 6  .30796  .50326/   .97846
 7    .00739  .05206   .01674
 8  .00739  .05700   .13222
 9  .00550  .06255   .01386
10  .00730  .00903   .00126
11  .02305  .08945   .00049
12  .03086  .33183   .04019
13  .02959  .13579   .33233
14  .02767  .23581   .01033
15  .07509  .28804   .00906

DOLD= 1.09230E-09  2.89947E-06
 -26  -3  107  -55  -41  12  -2
  -6  -51  32  -5  -61  1  6  9 -137 -26 -79
 -27  6  62  -2  120 -23  2 -13 -186  95  5 -54
-190 -18 -8  53 -67  34 -0  6 -71  -5 -23
-256 -42  46  7  3 -249  45 -3 -8 103 -131  -7 -31
113  -7  76  3  76 -206  60 -1 -34 -175 -97 -15 -51
-131 -56 167 -3  44
514 117  57  44
-1113 117  57 -3 -29  58
-1113  -3  -10 176  -41
-291 -30  -33 322  20
-309 -29  -55 295 -15
-212 -16 -67 -29 -33
145 260 -82
 0.0000000  0.0000000  0.0000000  0.0000000  0.0000000  0.00000544  0.0000000  0.00000056
```

PAR SEQ

16 17 36 35 34 33 3 4 2 1 31 30 29 28 18

DAMPED LEAST SQUARES

2.513E-45   3.011E-09   0.   0.   0.

5.019E-9

RAY 6 SURFACE 2GF

FOCUS

DOLD= 5.302134E-08

DOLD= 3.47131E-08   1.634069E-05

3 VIOL ATTEMPTED   9   0.   0.
2.553E-02   0.
2.611E-06   2.611E-08

FOCUS
6.000000 -0.000000 6.000000 0.000000 0.000000 0.00000

DOLD= 5.006616E-08

DOLD= 1.464610E-08   1.051420E-05

FOCUS
6.000000 6.000000 0.000000 0.000000 0.000000 0.000000 1.000000 0.00000

DOLD= 9.430033E-08

DOLD= 2.367573E-08   1.349522E-05

PAR SEQ

FOCUS

DOLD= 9.190001E-16

B VIOL ATTEMPTED
8.386E+00   6.199E-08   0.

6.199E-08

RAY 6 SURFACE 2CF

DOLD= 1.220766E-08 9.722063E-06

FOCUS

DOLD= 6.553091E-08

DOLD= 1.163494E-08 9.460421E-06
9.232E+01 6.274E-08   0.
6.274E-08   6.274E-08

6.274E-08
RAY 6 SURFACE 2CF

56

58

DOLD= 2.888189E-10 1.213947E-06

NRMV NLIM MRED RMSE Q1+2 Q2+2 VCR+2 CHNG+2 RED+2

RAY 6 SURFACE 2CF

RAY 26 SURFACE 2CF

RAY 6 SURFACE 2CF

FOCUS
.0107431 -.0075457 -.0574443 -.2302206 -.6698838 -5.4638955 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000

DOLD= 4.082362E-10
2   .47901   .38282   .34685
3   -.40385   .77920   .10769
4   .35962   .70062   .35765
5   .38264   .51968   .71722
6   -.00440   .05296   .10501
7   0.00000   .05081   .04342
8   -.00471   .05731   .02160
9   .00515   .05399   .04763
10 -.01027   .07763   .05593
11 -.02044   .09414   .02332
12   .03941   .12201   .14564
13 -.02749   .12560   .14567
14   .04087   .22854   .19763
15 -.07900   .23130   .04444

DOLD= 3.734259E-10   1.694847E-06

NU	NB	LB	LA	NI	NRMV	NLIM	NRED	RMSE+10	Q1+2	Q2+2	VCP+2	CHNG+2	PED+2
10	0	1	0	3	0	9	8	11965	100	0	33	8	8
10	0	1	0	3	0	9	8	11965	100	0	33	0	0
11	0	1	0	3	0	0	0	18024	99	0	99	0	0
41	0	1	0	3	0	0	0	9945	84	0	99	0	0
40	0	1	0	3	0	0	0	1955	92	0	99	0	0
-39	1	1	0	3	0	0	0	7745	96	0	99	0	0
38	0	-1	0	3	0	-1	0	1629	95	0	99	0	0
27	0	1	0	3	0	0	0	5567	92	0	99	0	0
-9	0	1	1	4	0	-1	0	65024	27	57	84	0	0
-5	0	1	1	4	0	-1	0	32343	63	0	97	1	3
7	0	1	1	5	0	-12	0	844491	19	11	18	1	1
2	0	1	1	4	0	0	0	7697	100	0	99	0	0
13	0	1	1	4	0	0	0	14717	42	0	98	0	0
12	0	1	1	5	0	0	0	91227	34	80	73	0	2

B VIOL. ATTEMPTED   14
LB VIOL. ATTEMPTED   14

22	0	1	1	5	8	-14	0	1001264	22	18	18	2	3
22	0	1	1	5	8	-14	0	1001264	22	18	18	2	3
4	0	1	-1	4	0	0	0	4745	100	0	99	0	0
3	0	1	-1	5	4	0	0	53056	26	98	10	0	0

| 30 | 0 | 1 | -1 | 6 | 12 | 0 | 2 | 2027 | 99 | 0 | 10 | 0 | 0 |

| 29 | 0 | 1 | -1 | 5 | 0 | 0 | 1 | 4188 | 96 | 0 | 99 | 0 | 0 |
| 28 | 0 | 1 | -1 | 4 | 29 | 0 | 0 | 52301 | 69 | 0 | 10 | 0 | 0 |

RAY 6 SURFACE 2CF

| 33 | 0 | 1 | -1 | 6 | 13 | 0 | 2 | 1671 | 98 | 0 | 10 | 0 | 0 |

| 16 | 0 | 1 | 0 | 4 | 0 | 0 | 1 | 4373 | 84 | 0 | 98 | 0 | 0 |

| 34 | 0 | 1 | 0 | 4 | 0 | 0 | 1 | 7268 | 51 | 0 | 93 | 0 | 0 |

RAY 6 SURFACE 2CF

| 35 | 0 | 1 | 1 | 8 | 0 | 0 | 3 | 200080 | 21 | 61 | 91 | 0 | 2 |

RAY 6 SURFACE 2CF

RAY 6 SURFACE 2CF

RAY 6 SURFACE 2CF

| 26 | 0 | 1 | 1 | 6 | 0 | -20 | 1 | 4227 | 10 | 14 | 62 | 0 | 1 |

| -18 | -1 | 1 | 1 | 9 | 26 | -2 | 3 | 1359 | 33 | 32 | 13 | 0 | 0 |

| 36 | 0 | 1 | 1 | 10 | 0 | -14 | 5 | 871 | 27 | 5 | 92 | 0 | 1 |

| 35 | 0 | 1 | 1 | 8 | 0 | -1 | 3 | 1176 | 15 | 25 | 74 | 0 | 0 |

| 34 | 1 | 1 | 1 | 6 | 0 | -1 | 1 | 2242 | 16 | 21 | 7 | 0 | 1 |

| -31 | 1 | 1 | 1 | 9 | 0 | 0 | 3 | 2161 | 17 | 12 | 0 | 0 | 0 |

| 33 | 0 | 1 | 1 | 6 | 2 | 0 | 1 | 1.28 | 40 | 72 | 86 | 0 | 0 |

FOCUS

67

1-14	0.	-.6500708	-0.	1.0000000	0.	0.	.0270047	0.
2	3.52503115E-01	3.94748330E-01	8.19151630E-01	9.909.0115E-01	-1.6900747E+00	0.
3	1.84009795E-01	1.34952306E-01	5.39009786E-01	1.617.4003E+00	4.50009066E-01	0.
4	3.62147431E-01	4.28266265E-01	7.91947930E-01	5.87977392E-01	-3.38713601E-02	0.
5	5.22276966E-01	9.11550006E-02	3.61136606E-01	5.41704964E-01	6.86589936E-01	0.
6	-3.10684903E-01	0.	30.1100000	0.	.1007172	0.
7	0.	.6599053	35.1100000	0.	.1007172	0.
8	-9.93291112E-01	0.	0.0000000	0.	.0270047	0.
9	3.93774045E-01	0.	60.0000000	0.	.0007053	0.
10	-1.04165110E+00	0.	0.0000000	9.56016333E+00	4.0025.355E+03	0.
11	-2.26979295E-01	-9.16422116E-02	-1.0506127E+00	-2.0429119E+04	-3.92144355E-01	0.
12	1.06098112E-01	2.13900110E-02	4.2739226E-03	6.4129006E-03	8.55099920E-02	0.
13	-3.49175570E-01	0.	0.0000000	0.	.0270047	0.
14	-6.05774172E-01	-1.69756110E-02	2.50712656E-01	5.30407475E-01	3.1010550E-01	0.
15	-4.17051572E-01	4.12500000E-06	8.250003865E-02	1.6556922E-01	2.24609979E-01	0.
16	-9.99999813E-01	0.	1.0000000	0.	.0270047	0.

17 : -1.41793772E-02 -4.817781855E-02 4.349701856E-03 0. 0.8666600 4.11234226E-03 4.50075966E-02

EFL,FP2,PP2   1.00000   3.78317   -.98455

SLOPE

DEPTH

HEIGHT

SURFACE 2 ONE SPACE EQUALS . 00452465

SLOPE

DEPTH

HEIGHT

SURFACE 14 ONE SPACE EQUALS .0005900

UPDATED VT PUNCHED

SINE(ANGLE)= .34202

Y,Z MICRONS,   PL MICRONSX100.

-50-----------40-------30-------20-------10-------0-------+10------+20------+30------+40-----+50

SAG FANY

SAG FANZ

MP FAN Y

PL MICRONS×100.

20---- Y,Z MICRONS,

SINE ANGLE= .64278

SAG FANY

SAG FANZ

MD FAN Y

YI,ZI MICRONS=10.PL=100.SCALE= 1.015E+02M

LENS TOLERANCE DATA

SCALE= 1.00 MM OR INCHES

FIELD ANGLE 1

PERTURBATION   TILT OF 1 ARCMIN   DISPLACEMENT OF .001IN.   TIR OF .001IN.
SUR TO SUR   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS

FIELD ANGLE 2

PERTURBATION   TILT OF 1 ARCMIN   DISPLACEMENT OF .001IN.   TIR OF .001IN.
SUR TO SUR   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS

FIELD ANGLE 3   .000149   .034565   .013847

PERTUBATION   TILT OF 1 ARCMIN   DISPLACEMENT OF .001IN.   TIR OF .001IN.
SUR TO SUR   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS

FIELD ANGLE 4

PERTUBATION   TILT OF 1 ARCMIN   DISPLACEMENT OF .001IN.   TIR OF .001IN.
SUR TO SUR   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS

FIELD ANGLE 5

PERTUBATION   TILT OF 1 ARCMIN   DISPLACEMENT OF .001IN.   TIR OF .001IN.
SUR TO SUR   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS

FIELD ANGLE 5
PERTURBATION   TILT OF 1 ARCMIN   DISPLACEMENT OF .0 1IN.   TIR OF .0 1IN.
SUR TO SUR   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS   RMS PL ERROR MICRONS

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